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STATISTICAL DESIGN OF ROCKFALL PROTECTIVE STRUCTURES USING A STOCHASTIC TRAJECTORY ANALYSIS MODEL

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ABSTRACT: Classically used trajectory analysis models do not really account for the stochastic nature of the trajectory of falling rocks related to the variability of the impact process. The presented work focuses on the bouncing phase modelling in the case of the interaction of a boulder with a coarse granular soil. Impact simulations are first held using a Discrete Element Method. A statistical analysis of the numerical results is performed in order to build a stochastic impact model relating boulder velocities before impact and after impact. The stochastic impact model is impended within a trajectory analysis software and a validation procedure using real-scale experiments is carried out. Finally, the stochastic trajectory analysis model developed allows characterizing probability distributions functions that quantify hazard levels on endangered slopes and allows defining a probabilistic framework for the optimization of protective structures design.

1 INTRODUCTION

The prediction of the trajectories of potentially falling boulders is one of the key points in the field of trajectory analysis. The large variability of slope properties and boulder removal conditions pleads for a stochastic modelling of these trajectories. In particular, the bounce of falling rocks has to be modelled as a random process (Laouafa and Nicot, 2003).

The aim of the present paper is to define a stochastic impact model that can precisely capture the variability of the bouncing phenomenon. The study focuses on modelling the impact when a boulder interacts with a scree slope. In this context, simulations are well adapted because they make it possible to obtain large sets of results under the same conditions, whereas results from rockfall events or field experiments are not directly usable because either the data set is incomplete (rockfall events) or reproducible impact conditions are difficult to obtain (field experiments).

In this paper, a numerical approach based on the Discrete Element Method (DEM) is used in order to investigate the impact of a boulder on a coarse granular soil. This model is used to perform an intensive simulations campaign. The analysis of numerical results from this campaign is carried out using advanced statistical methods leading to the definition of a stochastic impact model. The above mentioned stochastic impact model is finally integrated in the context of falling rocks trajectories simulations. The integration procedure is evaluated by comparing real-scale experimental results to rockfall trajectory simulations on the experimental site using this procedure. The use of the stochastic impact model in the context of trajectory analysis finally allows defining a global probabilistic framework dedicated to the

characterization of rockfall hazard and to the design of protection structures in terms of functional and structural efficiency.

2 STOCHASTIC IMPACT MODEL

Numerical modelling of the impact

Assuming that rocks composing the talus slope can be considered as rigid locally deformable two-dimensional bodies, the software Particle Flow Code 2D (Itasca, 1999) based on a Discrete Element Method (Cundall and Strack, 1979) is used. In the Discrete Element Method, contact forces are applied to neighboring particles in contact. In this paper, the normal and tangent contact forces acting between two particles are calculated using the Hertz-Mindlin model (Mindlin and Deresiewicz, 1953). The contact law only models frictional energy dissipation during the interaction of two rocks.

The mean diameter of soil particles is $R_m = 0.3 \text{ m}$ which corresponds to a relevant value for most of observed rockfall events. In addition, in the case of the impact of a boulder on a coarse granular soil, boulder and soil particles sizes are nearly the same. Boulder radius R_b therefore varies from R_m to $5R_m$. Sample properties are defined following the procedure used in Bourrier et al (2008). Once the sample is generated, impact simulations are held for varying impact points and incident kinematic parameters. Incident kinematic conditions are fully defined by the magnitude of the incident velocity V^{in} , the incident angle α^{in} and the incident rotational velocity ω^{in} (Figure 1). Finally, reflected velocities are collected when the normal component of the boulder velocity reaches its maximum.

It is important to note that the relevance of the DEM model has been proved compared to results from the literature (Bourrier et al., 2007) and from half-scale experiments of impacts on a coarse soil (Bourrier et al., 2008)].

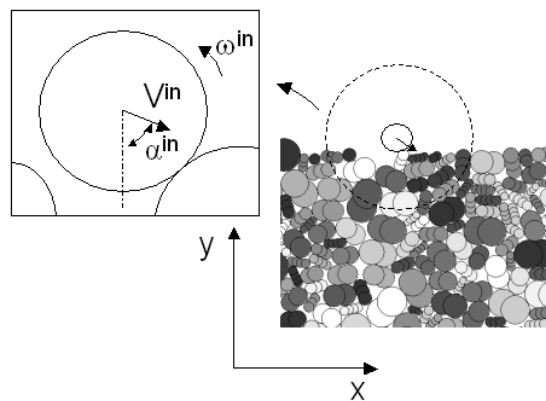


Fig. 1. Incident kinematics conditions.

Simulation campaign

Several impact simulations using the DEM model are conducted for varying impact points and incident kinematic parameters. Impact points are first precisely defined so that the same impact point can be used for several incident kinematic conditions: for a given impact point, a set of equally distributed incident kinematic parameters is explored ($5 \text{ m/s} < V^{\text{in}} < 30 \text{ m/s}$, $0^\circ < \alpha^{\text{in}} < 75^\circ$, $-6 \text{ rad/s} < \omega^{\text{in}} < 6 \text{ rad/s}$). Preliminary numerical investigations have shown that a minimum of 100 impact points have to be chosen to ensure stable mean values and standard deviations of the components of the reflected velocity (Bourrier et al., 2007). It is worth

noting that all impact points are located far enough from the lateral walls of the sample to avoid disturbances due to lateral walls (Bourrier et al., 2007).

The components of the reflected velocity of the boulder for all simulations performed allows building a database of numerical simulation results for varying impact points and incident kinematics conditions and for fixed soil macroscopic properties and boulder size.

Impact model formulation

Numerical results are treated in order to build a stochastic impact model relating incident and reflected kinematic parameters of the boulder. In a two-dimensional frame, kinematic parameters of the boulder are properly described by a generalized velocity vector \mathbf{V} that is composed of a velocity component v_y along the normal direction to soil surface, of a velocity component v_x along the tangent direction to soil surface and of a rotational velocity ω such as: $\mathbf{V} = (V_x \ V_y \ R_b \omega)^t$. The incident \mathbf{V}^{in} and reflected \mathbf{V}^{re} velocity vectors are related by the stochastic operator \tilde{f} :

$$\mathbf{V}^{\text{re}} = \tilde{f}(\mathbf{V}^{\text{in}}) \quad (1)$$

The first order Taylor series expansion of \tilde{f} defined in Eq. 1 leads to the definition of the operator \mathbf{A} composed of the coefficients a_i of the Taylor series expansion of \tilde{f} :

$$\mathbf{V}^{\text{re}} = \mathbf{A}\mathbf{V}^{\text{in}} \quad (2)$$

with,

$$\mathbf{A} = \begin{bmatrix} a_1 & a_2 & a_3 \\ a_4 & a_5 & a_6 \\ a_7 & a_8 & a_9 \end{bmatrix}$$

The high variability of the local configurations of the soil and of the incident kinematic conditions induces that the operator \mathbf{A} cannot be considered as a deterministic variable. A stochastic approach is therefore adopted in order to define a model that can capture the variability associated with the operator \mathbf{A} .

The operator \mathbf{A} is assumed to take a constant value \mathbf{A}_p for a given impact point p whatever the set k of incident kinematic parameters. The dependence between the values of the coefficients of the operator \mathbf{A} for varying impact points p is captured using a normal probability distribution function characterized by a mean vector \mathbf{M}^α and a covariance matrix Σ^α .

For such models, classical estimation such as likelihood maximization can be very tricky. On the contrary, the parameters \mathbf{M}^α and Σ^α can easily be estimated using Bayesian inference (Bayes, 1763). For instance MCMC algorithms can be run under the free software Winbugs® (Spiegelhalter and al., 2000). The determination of the parameters \mathbf{M}^α and Σ^α of the stochastic impact model first highlights that, whatever the macroscopic soil properties and the impacting boulder size, more than 75% of the variability of the reflected velocity vector is captured. In addition, the study of the influence of macroscopic soil properties and boulder radius on \mathbf{M}^α and Σ^α shows that these parameters mainly depend on the ratio R_b/R_m , the porosity, the sample depth and the soil particles shape.

Contrary to standard models, the mean restitution coefficients R_t and R_n predicted by the model are not constant values; they depend heavily on all the incident kinematic parameters (Bourrier et al. 2007). Moreover, contrary to classical approaches, the model proposed is

directly developed in a global stochastic framework. The stochastic impact model proposed therefore constitutes an extension to classical models that traduces the coupling between the incident kinematic parameters and allows precisely describing the variability of the reflected velocity.

3 APPLICATION TO TRAJECTORY ANALYSIS

The stochastic impact model is integrated in a 3D rockfall simulation model called Rockyfor (Dorren et al., 2004; Dorren et al., 2006). The numerical results obtained are compared to results from real-scale rockfall experiments.

Real-scale experiments

The experimental site (Dorren et al. 2006) is located in the ‘Forêt Communale de Vaujany’ in France (lat. $45^{\circ}12'$, long. $6^{\circ}3'$). The study area covers an Alpine slope ranging from 1200 m to 1400 m above sea level with a mean gradient of 38° . The experimental site is part of a hillslope that is formed by a huge post-glacially developed talus cone mainly consisting of rock avalanche, snow avalanche and rockfall deposits. It covers an avalanche *couloir* and is therefore denuded of trees.

During all the experiments, the protocol was identical. Before each single rockfall experiment, the volume of the rock to be thrown was estimated by measuring the height, width and depth along the three most dominant rock axes. A total of 100 rocks were released individually, one after the other. The mean volume of the rocks was 0.8 m^3 and the standard deviation 0.15 m^3 .

A front shovel was used to throw the rocks down the slope, starting with a freefall of 5 m. The stopping points of the rocks were captured. In addition, rockfall trajectories were filmed by five digital cameras, which were installed along the experimental site. Additional details on the experiments are given in Dorren et al. (2006).

The simulated distributions of the maximum rebound heights H^{max} and maximum translational velocity V^{max} are compared to observed distributions of those variables at one “Evaluation Line” (EL1), located after 185 m from the starting point. In addition, the trajectories of the simulated rocks are compared to the experimental stopping points.

Integration procedure

As input data for the simulations carried out in this study, the trajectory analysis software RockyFor first requires a Digital Elevation Model in which the topography and the rockfall source locations are defined further to a field survey.

A database composed of several sets of parameters a_i for varying values of the ratio R_b/R_m comprised between 1 and 5 is built. For this purpose, DEM calculations are performed which necessitates evaluating the porosity of the soil, the depth of the soil and the particles shape corresponding to the study site. As, for each rebound calculation, the choice of the values of the parameters a_i depend on the value of the ratio R_b/R_m , a field survey is conducted in order to determine all the values of R_m for all the spatial coordinates in the study site. Additionally, for each rockfall simulation, the boulder radius R_b is extracted from the distribution measured in the experiments.

In a 3D context, the tangential and normal to soil surface components of the incident velocity vector allow defining a plane called incident plane. Similarly, the tangential and normal components of the reflected velocity also allow defining a plane called reflected plane. The angle δ^{re} between these two planes is called deviation angle. In addition, the assumption is made that, before (resp. after) impact, the block’s rotation axis is perpendicular to the incidence (resp. reflected) plane (Figure 2).

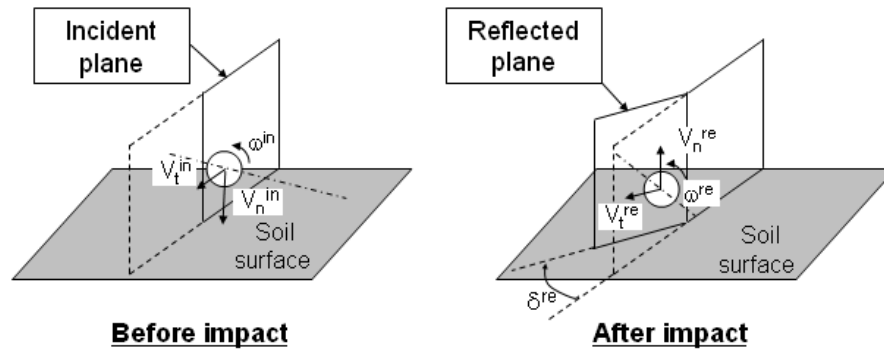


Fig. 2. Definition of the incident and reflected planes.

For each rebound of the boulder, the calculation of the reflected velocity vector from the incident velocity vector is performed in two stages. The components of the reflected velocity vector in the reflected plane are first calculated from the components of the incident velocity vector in the incident plane using the stochastic impact model. For this purpose, the R_b/R_m ratio is first determined. This allows choosing a set of parameters a_i corresponding to the ratio R_b/R_m calculated and calculating the reflected velocity using the chosen set of parameters a_i . In the second stage of the determination of the reflected velocity vector, the deviation angle δ^{re} is calculated. The deviation angle δ^{re} is determined by a random number that defines if the rock is deviated, either between 0 and 22.5° from its original direction towards the steepest slope direction, or 22.5 – 45°, or 45 – 55°. The first case has a probability of occurrence of 74%, the second case 24% and the third case 4% (Dorren et al., 2004). 10,000 falling rocks were carried out using the above mentioned procedure.

Procedure validation

The comparisons between the experimental and simulated results at EL1 show that both the mean values and standard deviations are predicted accurately for rock passing heights and translational kinetic energy (Table 1). The shapes of the distributions of the simulated quantities are very similar to those obtained in the experiments, although the reduced number of experiments does not fully allow determining the complete distribution (Figure 3).

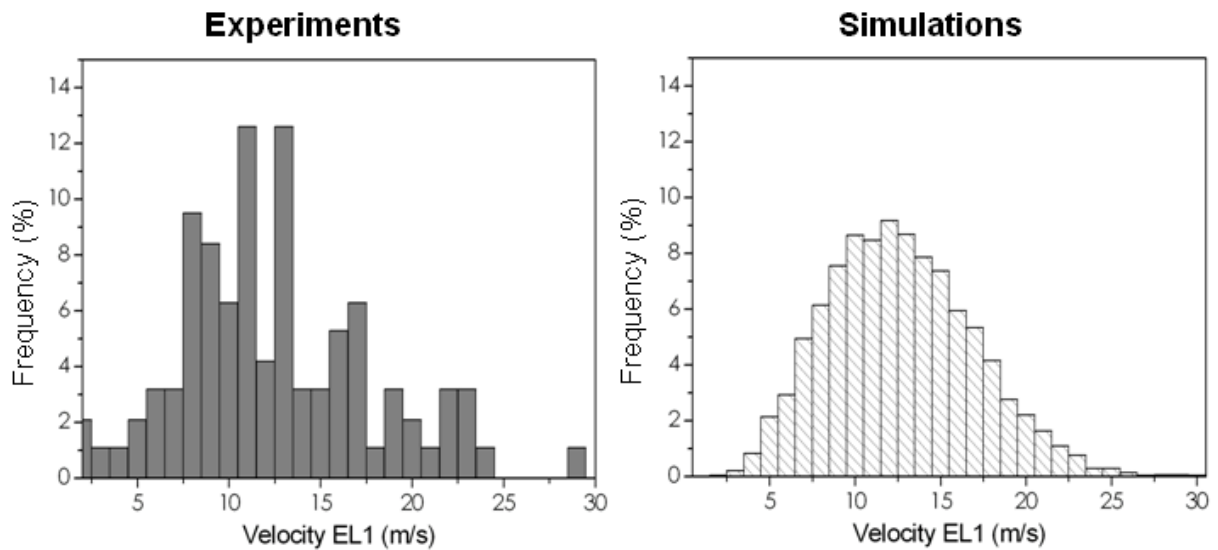


Fig. 3. Distribution of the falling rock velocity at EL1 in the experiments and in the simulations.

Table 1. Relative errors (RE) compared to experimental distributions of H^{max} and V^{max} at EL1.

RE H^{max} at EL1 (%)		RE V^{max} at EL1 (%)	
Mean	Standard deviation	Mean	Standard deviation
0	-9	4	-10

The 3D comparison between simulated passing frequencies and experimental stopping points provides interesting information (Figure 4). First, the simulated runout zones are larger than the experimental ones. Indeed, the maximum runout distance obtained in the simulations is associated with a probability of 1/10,000 that a rockfall event occurs as 10,000 simulations were performed. On the contrary, as the real scale experimental campaign consists of 100 rockfall experiments, the maximum runout distance obtained in the experiments is associated with the 1 % pass frequency limit. However, the limit for which the probability of a simulated falling rock event is smaller than 1/100 (1 % pass frequency limit) approximately corresponds to the experimentally observed stopping points.

The difference between simulated and experimental maximum runout zones can be explained by the fact that the stochastic impact model is not adapted for fine soils, which are found in the valley bottom. The difference between the experimental and simulated runout zones patterns can also result from an imperfect digital representation of the terrain in the DEM at the intersection of the avalanche path and the forest road. This local discrepancy in the DEM results from its spatial resolution.

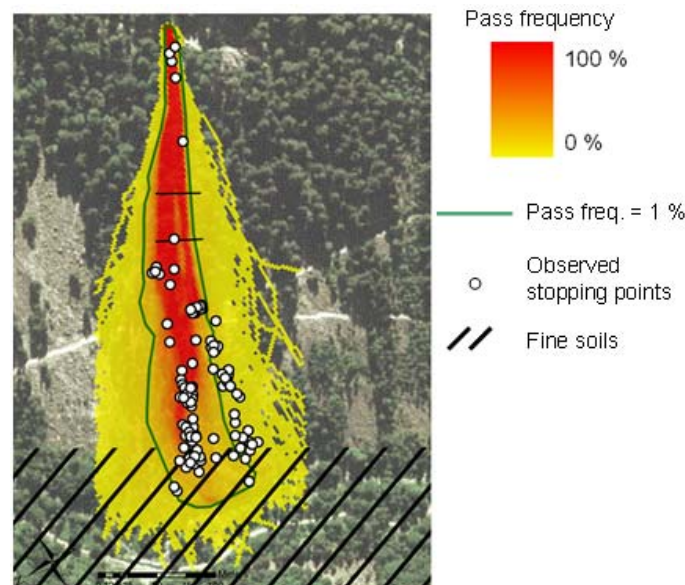


Fig. 4. Map of the simulated pass frequencies and observed stopping points.

4 ROCKFALL PROTECTIVE STRUCTURE DESIGN

The comparison to real scale experiments proved that the use of the stochastic impact model for trajectory analysis allows accurately approaching the distribution of the trajectories of the falling rocks. On the basis of this procedure, a probabilistic framework for rockfall hazard calculation is developed in order to optimize the positioning and the design of protection structures.

The probabilistic framework developed is illustrated using a 2D example (Figure 5). In this illustrative example, the study performed aims at protecting an element at risk located at an horizontal distance $x = 140 \text{ m}$ from a rockfall source from which rocks detach starting with a 5 m high freefall. The radius of the falling rocks is assumed to be 0.5 m . The study site is composed of a homogeneous slope (100 m long, 35° slope) followed by a valley bottom. The mean size of soil particles is assumed to be $R_m = 0.25 \text{ m}$ along the slope and $R_m = 0.1 \text{ m}$ in the valley bottom.

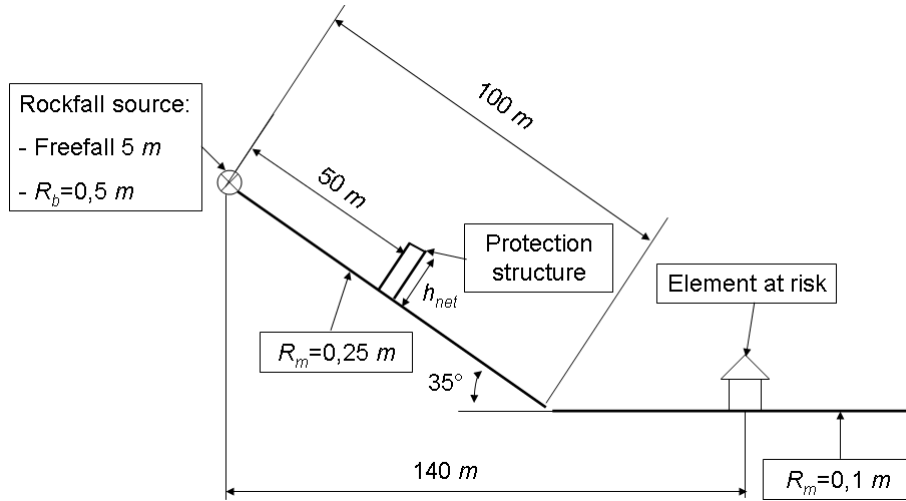


Fig. 5. Study site in the illustrative example.

Rockfall hazard determination

Rockfall hazard $A(x)$ is defined as the conjunction of the probability $P(D)$ for a rock to detach from the cliff with the probability $P(x)$ for the rock, once detached, to propagate through a point located at an horizontal distance x from the rockfall source:

$$A(x) = P(D)P(x) \quad (3)$$

In this example, the detachment probability $P(D)$ is assumed to be 1 in order to focus on the probability $P(x)$. $P(x)$ is calculated by integrating the local probability $p(Ec, x, y)$ towards to the passing rock kinetic energy Ec and the vertical coordinate y :

$$P(x) = \iint p(Ec, x, y) dy dEc \quad (4)$$

$p(Ec, x, y)$ is the probability for the falling rock to pass through the point (x, y) with a kinetic energy Ec . The probability $p(Ec, x, y)$ is directly obtained from rockfall trajectory simulations. The integration of this local information leads to the calculation of rockfall hazard $A(x)$ depending on the horizontal distance from the rockfall source (Figure 6).

In France, rockfall hazard characterization is usually based on the association of rockfall hazard classes with each point of a study site. A rockfall hazard level is attributed to each point of the study site depending on the value of the rockfall hazard $A(x)$. If $A(x)$ is larger than 1%, the point is associated with high rockfall hazard level; if $0.01\% < A(x) < 1\%$, it is associated with medium hazard level and, if $A(x)$ is smaller than 0.01%, a low hazard level is attributed to the point considered.

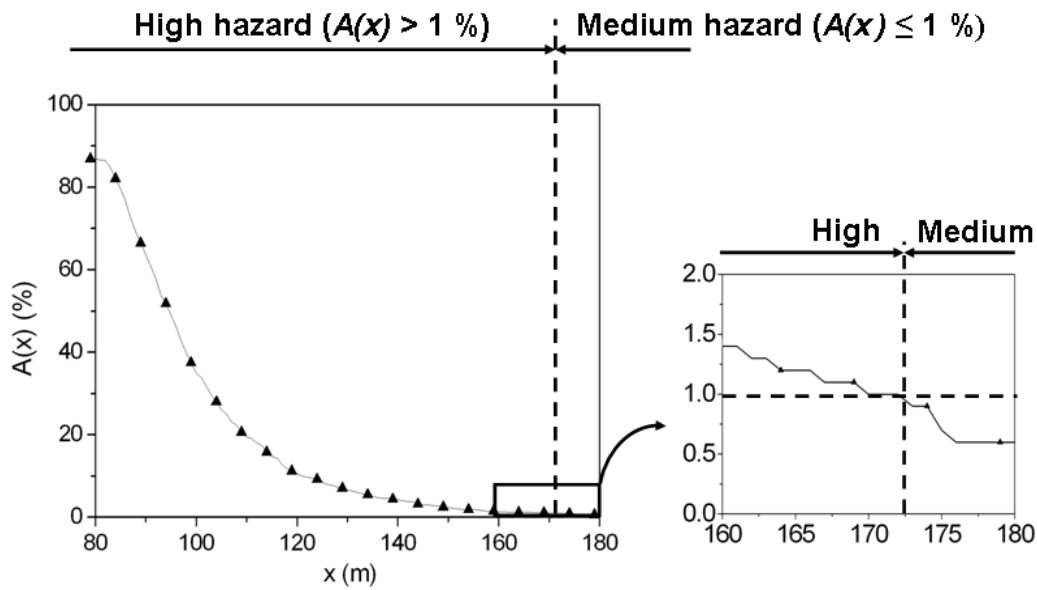


Fig. 6. Rockfall hazard $A(x)$ depending on the horizontal distance x from the rockfall source.

In the illustrative example, the element at risk is associated with a high hazard level because, as it is located at $x = 140 \text{ m}$ from the rockfall source, $A(x) = 4.3\%$ which is larger than 1% (Figure 6). The aim of the approach presented here is therefore to design a rockfall protection structure capable of reducing the hazard level at the element at risk. The assumption is made that the hazard level must be reduced from high to medium level.

Rockfall protection structure design

The choice is made to protect the element at risk by integrating rockfall restraining nets 50 m, measured along the slope, after the rockfall source. The probabilistic approach proposed aims at calculating the height h_{net} of the nets in order to reduce rockfall hazard at the element at risk ($x_e = 140 \text{ m}$) below the value of 1% so that hazard level is reduced to medium class. Different trajectory simulations are performed in which restraining nets (with various heights h_{net}) are integrated. In these simulations, the assumption is made that the nets were designed to stop the impacting rocks whatever the impacting kinetic energy.

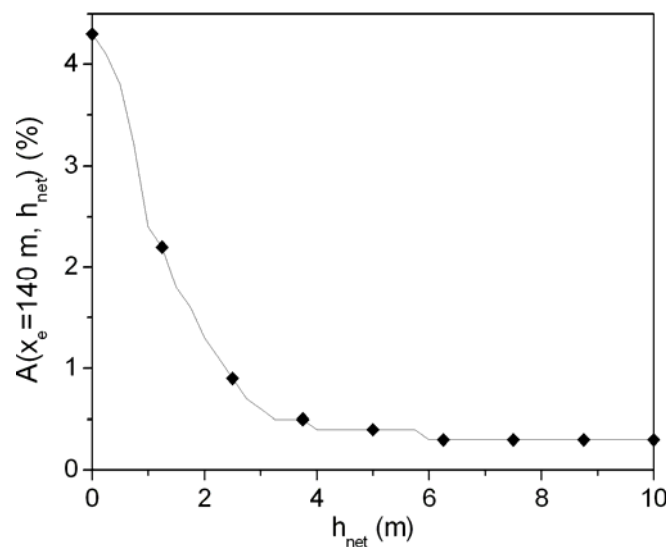


Fig. 7. Hazard $A(x_e = 140 \text{ m}, h_{net})$ at the element at risk depending on the height h_{net} of the integrated nets.

The numerical results obtained allow calculating the evolution of the hazard $A(x_e = 140 \text{ m}, h_{net})$ at the element at risk depending on the height h_{net} of the integrated nets (Figure 7). The results show that a minimum nets height of $h_{net} = 2.5 \text{ m}$ is necessary to reduce the hazard at the element at risk from high to medium level ($A(x) \leq 1\%$).

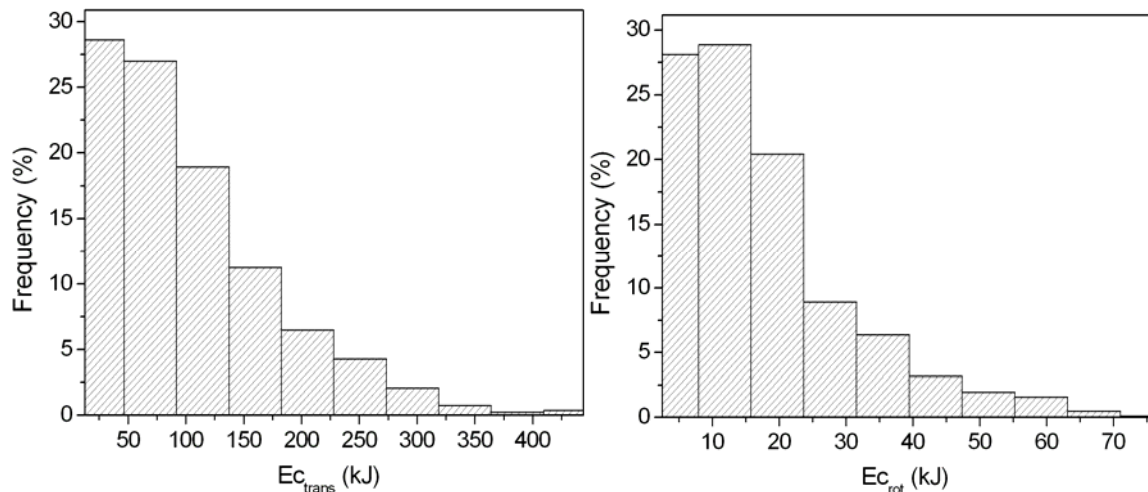


Fig. 8. Distributions of the translational $E_{c_{trans}}$ and rotational $E_{c_{rot}}$ energies impacting the nets ($h_{net} = 2.5 \text{ m}$).

The probabilistic framework proposed also provides interesting information for the probabilistic design of the protection structure in terms of structural efficiency. Indeed, as the use of this framework provide relevant rocks passing frequencies and passing energies distributions, the calculated distribution of the kinetic energy impacting the protection structure can be used with confidence. In addition, contrary to usual trajectory simulations, the rotational velocity of the falling rock is calculated in the proposed approach. As a result, the distributions of both the translational $E_{c_{trans}}$ and the rotational $E_{c_{rot}}$ kinetic energies impacting the protection structure can be determined (Figure 8).

These distributions are essential for designing effective protective structures. The translational kinetic energy mainly determines the design of the structure (structural strength performance), whereas the rock's rotational kinetic energy determines the capability of the structure to prevent rocks from rolling over the structure (structure shape efficiency). In addition, these distributions provide loading cases for the probabilistic design of the protection structure.

5 CONCLUSION

In this work, the impact of a rock on a scree slope is modelled using the Discrete Element Method. An intensive simulation campaign is performed providing a large set of results for impacts associated with different soil particles spatial configuration and boulder incident kinematic parameters. Assuming that a relation exists between the incident and reflected kinematic parameters of the falling rock, the statistical analysis of numerical results using Bayesian inference leads to the definition of a stochastic impact model. This model is relevant for rock velocity after impact depending on both rock velocities before impact and soil particles layout near the impact point.

Finally, the stochastic impact model is integrated into a trajectory analysis model. The comparison of the predictions of this model with results from real-scale experiments shows that the procedure developed allows predicting the distribution of falling rocks trajectories. The stochastic feature of this new trajectory simulation model also allow defining a

methodology for the probabilistic characterization of rockfall hazard which offers a complete dataset for positioning and designing rockfall protective structures. We believe that such approaches should form the basis of future hazard mitigation paradigms.

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