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Effect of the number of simulations on the accuracy of a rockfall analysis

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Abstract

The reliability of the results of a probabilistic rockfall analysis mainly depends, among other factors, on the number of simulations of boulder trajectories along the slope. Depending on the input parameters of the analysis, the minimum number of simulations necessary to obtain reliable results in terms of boulder velocity, energy or rebound height can be very different. In this paper, a methodology is proposed to relate the expected error on the results of the analysis and the number of simulations. The methodology is exemplified with reference to the *Rockyfor3D* code. The results are statistically elaborated through the Kolmogorov-Smirnov method, in order to identify the minimum number of simulations required to maintain the error lower than a threshold value. A preliminary investigation on the possibility to relate this number to some input parameters of the analysis is finally presented and discussed.

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1. Introduction

The territorial protection from rockfall and the design of protection fences need for quantitative analyses of the effects that the boulders detached from the slope, with its collision, cause to the exposed elements. To this aim, the evaluation of boulder trajectories along the slope and the associated kinetic energy is essential [1,2]. The description

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of evolution of fragmental rockfalls in space and time relies on the laws of mechanics [3,4,5,6], and can be performed with different complexity by means of empirical relations [7], kinematic, [8,9,10], or dynamic models [4,5,11,12]. These aspects can be evaluated in a probabilistic way by using provisional models that simulate rockfall phenomena through the analysis of their different phases: detachment, free fall, rebound, rolling and sliding.

The high computational costs related to the modelling of slope surface often induce to simplify the problem: trajectories can be modeled in 2D along one or more slope profiles, the characteristics of the fallen blocks can be neglect (lumped mass methods), the interaction between block and slope can be simplified [13].

However, a detailed analysis of the problem needs to consider its tridimensional characteristics together with all the factors that influence the behavior of the fallen block and their statistical variability. This leads to the need of repeating trajectory simulations an adequate number of times, to obtain a reliable statistical result in terms of velocity and kinetic energy of the block along the entire slope.

The aim of this work is to identify the minimum number of simulations required to obtain results with an error lower than an established value, or a given variability of the results, as a function of the principal parameters of the analysis. A methodology based on the Kolmogorov-Smirnov method [14] is presented and some preliminary results related to the dependence of the results on the density of vegetation (forest) on the slope are discussed. Rockfall analyses are carried out through the Rockyfor3D code [15] on a simplified slope composed by three planar surfaces with different declivity in order to reduce uncertainty due to topographical factors.

2. Description of the rockfall scenarios

Rockfall simulations were carried out on a simplified slope composed by three planar surfaces with different declivity: the detachment area (A), the run-out area (B) and the stopping area (C) (Fig. 1a), discretized in a DTM with a resolution 5m x 5m. The main slope and forest characteristics are listed in Tab. 1.

Table 1. Characteristics of the analyzed slope.

Slope area	Description	Density of vegetation (tree/ha)	Coniferous percentage (%)	Diameter (cm)
A	Compact soil with large rock fragments	0	100	35
B	Compact soil with large rock fragments	0÷10000	100	35
C	Fine soil material	0÷10000	100	35

As shown in Fig. 1a, a source point (consisting in a single DTM cell) is located on surface A, while a fictitious collector net is located at the bottom of surface B in order to obtain information on the characteristics (rotational and translational velocity, kinetic energy, crossing height, and crossing angle) of each block trajectory that crosses it. A cubic block was considered, with volume equal to 1 m3. Finally, a very large number of simulations (100000) were carried out from the source point, in order to cover all the possible variability of block trajectory.

Among the input data needed for the analysis, most relevant is the density of vegetation (forest) on the slope. Rockyfor3D allows to consider this aspect in terms of number of trees per hectare (trees/ha). In the first step of this work, a parametric analysis was carried out through the variation of the density of vegetation associated to the runout and stopping zones of the slope (surfaces B and C). A range from 0 trees/ha to 10000 trees/ha was taken into account with the aim to investigate its effect on the results of the analysis. In the following, the results are presented in terms of translational velocity of the block, one of the most significant parameters for the design of protection measures. All the other variables computed at the collector can be analyzed in the same way. In Figs. 1b and 1c the distribution of the maximum simulated velocity along the slope is shown, with reference to the scenario without forest (Fig. 1b) and with 400 trees/ha, i.e. 1 tree per DTM cell (Fig. 1c).

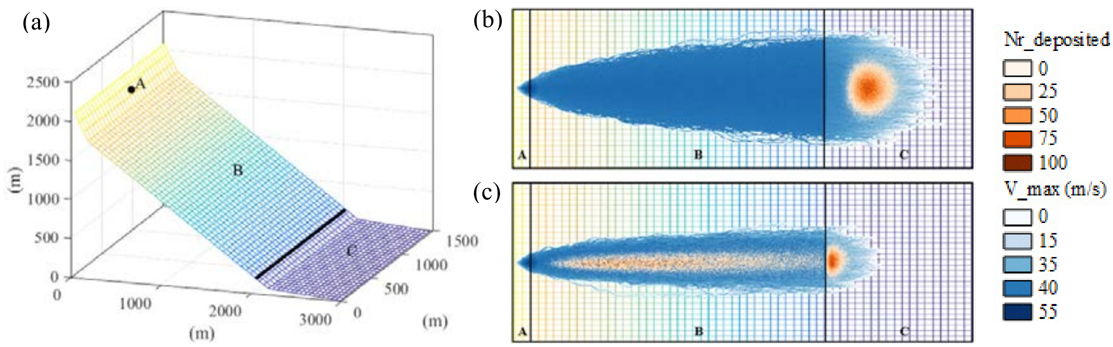

Fig. 1. (a) Simplified analyzed slope with indication of the source point and the collector net; Distribution of the maximum translational velocity (m/s) along the slope and of the number of deposited blocks: (b) in the case of absence of trees and (c) in the case of 400 trees/ha on surfaces B and C.

The number of deposited blocks is also indicated in both the figures. It can be observed that, when density is very high, the effect of the forest on the slope is to decelerate or stop blocks, rather than deviate them.

Fig. 2a shows the distribution of translational velocity at the collector net, considering all the trajectories that intercept the collector, for all the tree density scenarios considered in the parametric analysis. With increasing the density of trees, the number of the intercepted trajectories decreases since the trees located on plane B stop many blocks. For example, in the case of absence of trees all the 100000 simulated trajectories cross the collector, while in the case of 400 trees/ha only 29255 trajectories reach the collector (Tab. 2).

Table 2. Block trajectories that reach the collector for each tree density scenario.

Scenario (trees/ha)	0	100	150	200	250	300	350	400	1000	2500
Number of block trajectories	100000	99999	99988	99626	96205	82902	57786	29255	29927	29817

Moreover, with increasing the density of trees, the mean value of the distribution decreases until the value of 400 trees/ha (passing from 39.11 m/s for the scenario without trees to 22.3 m/s for the scenario with 400 tree/ha). On the contrary, its variance increases from 6.45 m/s to 41.63 m/s. Overcoming 400 trees/ha (i.e. 1 tree/cell), both the mean and the variance of the distribution remain unvaried (Fig. 2b). This seems to indicate 1 tree/cell as a critical value of the analysis. This aspect will be better investigated in the future.

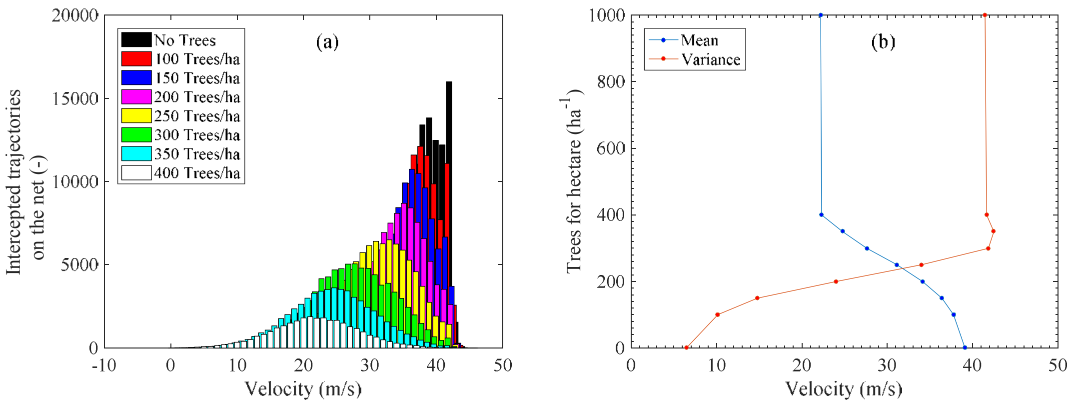

Fig. 2. (a) Distribution of block translational velocity at the collector for different forest scenarios on the slope; (b) variation of mean and variance of the distributions.

3. Statistical analysis

With the aim to evaluate the error involved by a reduced number of simulations, a comparison between the shapes of the cumulative distributions at various number of simulations was made. The comparison was done in terms of a Kolmogorov-Smirnov metrics, i.e., the supremum distance between two empirical distribution functions [14]. Starting from a set of data, made of the results of all the trajectories that cross the collector (Tab. 2), a subset of 50 elements was randomly extracted through the Monte-Carlo procedure. Defining Ppop the empirical distribution of the original set of data and Pev the empirical distribution of the extracted subset, the maximum discrepancy between the distributions was evaluated:

$$max\left|P_{ev}(X)-P_{pop}(X)\right| \tag{1}$$

Note that in (1) the discrepancy was defined in terms of the value of the probability. This operation was repeated 1000 times in such a way that 1000 maximum discrepancies were found. A statistics on these maxima was done, as illustrated in the following. In parallel, the discrepancy was evaluated in terms of the value of the statistic X, i.e.

$$max\left|X_{ev}(P)-X_{pop}(P)\right| \tag{2}$$

The procedure was repeated e number of times, in order to compare different subsets of elements (e.g. 50, 100, 200, 300 elements). In Fig. 3(a), with reference to the translational velocity at the collector, the cumulates of frequency of the maximum difference in terms of discrepancy on the probability of occurrence P is shown for each subset, following Eqn. (1). In the same way, in Fig. 3(b) the cumulates of frequency of the maximum difference in terms of discrepancy on the value of the velocity X are shown, following Eqn. (2). These cumulates allow, by a different number of simulations, to define the probability to obtain an error lower than an established value (%) or the probability to obtain a variability of the parameter lower than an established value.

For example, entering in the graph of Fig. 3(a) with a selected value of the error, the curves represent the probability that the result belongs to this error. Choosing a threshold error of about 10% in terms of probability, the probability that, performing 50 simulations, the value of block velocity at the collector will be lower than the threshold is about 50%. It increases to 80% with 100 simulations, to 95% with 200 simulations and is very close to 100% with 300 simulations. Figs. 3(a) and (b) are referred to the translational velocity at the collector, all the other results of the rockfall analysis (e.g. kinetic energy or crossing height) can be studied in the same way.

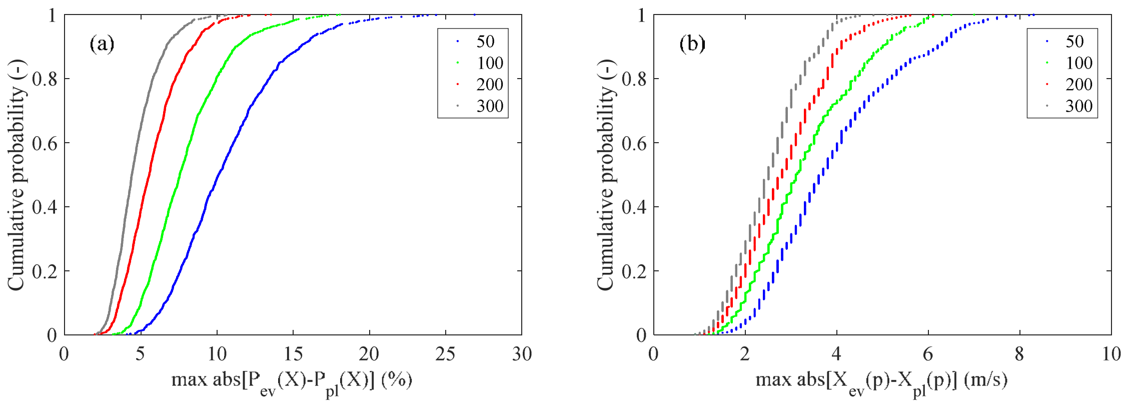

Fig. 3. Cumulates of frequency for different subset of elements: (a) maximum error (%); (b) maximum difference on the value of the parameter.

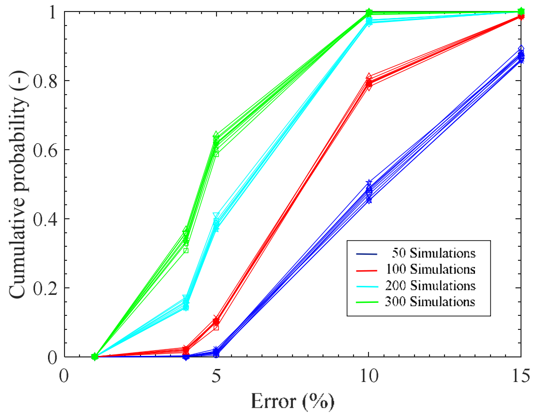

Fig. 4. Summary of the results of the statistical analysis related to block translational velocity: probability to obtain an error lower than a given value as a function of the density of vegetation and of the number of simulations.

The proposed statistical procedure can be used to evaluate the reliability of the rockfall analysis as a function of the number of simulations carried out. On the basis of the assumption that the input parameters of the analysis can influence such reliability, i.e. can affect the error made through a limited number of simulations, the following step of the work was to investigate on the role of some characteristics of the slope and the falling block. The statistical analysis was therefore conducted for the simulations scenarios described in Section 2, characterized by different density of vegetation, in order to compare the results and to study the effect of the presence and the density of a forest on the reliability of the analysis.

However, the results of this comparison seem to indicate a very limited influence, as shown in Fig. 4, where each colored envelope represents the results of the statistical analyses carried out for the different scenarios of density of vegetation (0÷400 trees/ha). With the same number of simulations, the probability to obtain the velocity at the collector with an error lower than a given value changes very little with varying of the density of vegetation. For example, assuming a threshold value of the expected error of 10%, in the case of 50 simulations, the probability to obtain an error lower than the threshold is included in a range of 45%-50% for any forest scenario. This range decreases with increasing the number of simulation (78%-81%) in the case of 100 simulations, (97%-98) in the case of 200 simulations, (99%-100%) in the case of 300 simulations

The same results were obtained with the other results of the analysis, such as the kinetic energy of the block, the height and the angle of impact on the collector.

4. Discussion and conclusion

The difficulty to run a reliable probabilistic rockfall analysis, related to the choice of the minimum number of individual trajectories to be simulated, led this study. A procedure was therefore proposed to correlate the number of simulations to the precision of the results in terms of statistical distribution of block velocity, kinetic energy, impact height and inclination.

The study was carried out through the Rockyfor3D code [15] that needs detailed input parameters for the block's characteristics (shape, volume), and for the slope's conditions (roughness, soil type, density and characteristics of vegetation). When possible, the setting of these parameters is usually conducted by back analyses of occurred events. However, this is a very complex process with remarkable uncertainties related to the great number of variables and to their intrinsic variability. An additional source of uncertainty is given by the number of simulation carried out in the analysis, i.e. the number of block trajectories simulated. In the case this number is too small, the reliability of the whole analysis can be strongly affected.

The proposed procedure, based on the Kolmogorov-Smirnov method [14], allows to evaluate the probability to obtain an error lower than a given value on the results of the analysis as a function of the number of simulations. A prior rockfall analysis, based on a number of simulations large enough to obtain a reliable population of the results is needed. The procedure can be used by the software's users to set the analyses as a function of the expected results, in relation to the aim of the analysis itself (e.g. barriers design, land planning, etc.).

Finally, with the aim to evaluate the influence of the input parameters of the analysis on the error, it was also presented a preliminary application of the methodology to a simplified slope where the density of vegetation was parametrically varied in a range 0÷10000 trees/ha. The first results indicates that this slope characteristic has an important role on the results of the analysis but it does not seem to have the same role on the error obtained through a limited number of simulations.

The same investigation will be carried out with reference to other factors influencing the rockfall analysis such as the volume of the block, its shape, and the roughness of the slope, in order to define a framework useful to the operators to set the rockfall analysis.

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