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The role of block shape and slenderness in the preliminary estimation of rockfall propagation

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Abstract. Among the wide range of variables that influence the falling process of blocks during a rockfall event, the shape of the block often plays a crucial role. Spherical-like blocks typically reach longer runout distances while elongated and plate volumes stop earlier. Nevertheless, with reference to runout modelling and hazard analyses, the shape of the block was disregarded for very long time until the last two decades when more rigorous rockfall models were developed. Nowadays fully 3D rigid body models and particle-based ones can take into account different and complex aspects related to block geometry and size (e.g. shape, change of shape, slenderness, fragmentation, etc.) when in site-specific applications are addressed. On the other hand, when the rockfall analysis is extended over large areas, simplified runout models can be used for preliminary, quick analyses, aimed at highlighting the most critical zones of the area. In this case, the variables that influence the rockfall process should be included in the analysis in equivalent terms. Among these simplified models, the Cone Method allows to reduce the runout phase to an equivalent sliding motion of the block along an inclined plane. The inclination of this plane with respect to the horizontal plane (i.e. the energy angle ϕ_p) can be related to both block and slope properties of the real rockfall case. The authors of this paper developed a methodology for the estimation of the energy angle as a function of the condition of the site under analysis (characteristics of the blocks and the slope), to be used for preliminary forecasting analyses at medium-small scales. To this aim, a series of parametric analyses have been carried out to quantify the role of each variable on the energy angle. In this paper, the role of block shape and slenderness (i.e. the ratio between the height and the width of the rock block) is analysed via several propagation analyses carried out on simplified synthetic slopes by using the fully 3D RAMMS::ROCKFALL model. The results were finally statistically treated in terms of energy angles in order to take into account the variability of rockfall trajectories and provide a contribution for the estimation of the parameters within preliminary analyses based on the Cone Method.

1. Introduction

In the framework of rockfall analyses, it is largely known that the characteristics of the falling blocks (volume, shape and slenderness) strongly influence their trajectories, stopping points and, therefore, the spatial extension of the invasion zones. Many authors, starting from a large number of in situ observations, indicated that there is a gradual increase of deposited boulder size moving downward along the slope [1-3]. The effect is a longitudinal sorting of block volumes downslope in which the largest sizes reach farthest distances with respect to their detachment points. Messenzehl and Dikau [4] found that the growing of the block size distribution is accompanied by an increase in the sphericity of the blocks. This latter aspect was reported by many researchers and can be explained with the fact that boulders with rounded shape tend not to lose their momentum when falling down [5,6]. Moreover, Nagendran and Ismail [7] indicated that spherical-shaped rocks have a higher chance of rolling further away than blocks with high angularity. On the contrary, angular blocks with sharp edges and flat surfaces generate higher frictional forces at the contact with the slope surface. Also, the slenderness of the blocks shows an interesting effect on the runout distances. Generally, platy and elongated (high slenderness) blocks reach the shortest runout distances because of the higher contact surface and the faster dissipation of momentum during the descent [3,5].

In site-specific rockfall analyses, the problem of block characteristics is typically faced with 3D mechanical models in which the inertia of the block is considered through rigid body considerations, and very detailed analysis of block impact on the ground can be carried out [8]. On the other hand, simplified models used at small scale of analysis cannot take this topic into account and typically resort to precautionary assumptions [9]. For instance, lumped mass trajectographic models assume blocks as dimensionless points allowing only to simulate their mass, or the simpler mechanical-based Cone Method simulates the complex descent trajectory of the block as an equivalent sliding motion along an inclined line (energy line) without directly considering any block features. In these cases, the role of block shape and volume must be taken into account indirectly, through a proper calibration of the restitution coefficients (lumped mass models) or a reliable definition of the energy line (Cone Method).

In particular, the energy line connects the rockfall source to the stopping point (figure 1) and its inclination therefore assumes the meaning of global friction angle. To take into account the variability of rockfall trajectories within the Cone Method [10], a cone can be defined with apex in the source point, whose dimensions are such as to envelope all the possible energy lines generated from that point. The potential invasion zone of a rockfall event generated from the source can be described as the intersection between this cone and the topographical surface of the slope. The cone is completely defined in 3D space by using the dip direction angle θ (defining the orientation of the cone axis with respect to the North) and two "cone angles": the energy angle ϕ_p and the lateral angle α, defining the steepness of the cone with respect to the horizontal plane and the lateral spreading around the cone axis, respectively. In particular, the energy angle has to take into account all the dissipative phenomena occurring during the descent path of a rock block along a slope and related to both the slope and boulder properties. The Cone Method was recently implemented by Castelli et al. [11] in the QGIS-based plugin QPROTO [12].

In order to perform reliable forecasting analyses of rockfall activity with the Cone Method, the main input parameters (i.e., the cone angles) have to be related to both slope and block features. To achieve this goal, the authors of this work have started a set of sensitivity studies devoted to the assessment of the influence of different factors on cone angles with particular reference to the plugin QPROTO [11,13]. In this paper, the authors propose a quantitative and statistical methodology which is able to relate the variation of some geometrical block characteristics (i.e., shape and slenderness) to the corresponding values of the energy angle (ϕ_p). Therefore, a series of trajectographic simulations were carried out with the fully 3D RAMMS::ROCKFALL model [14,15] on artificial synthetic slopes. The output of this activity was statistically treated to provide the QPROTO users a contribution for the definition of the parameters within quick and reliable rockfall susceptibility and hazard analyses.

2. The proposed methodology

In order to relate the shape and the slenderness of the block to the main parameter of the Cone Method i.e., the energy angle ϕ_p, a quantitative semi-statistical method have been developed. The method is based on a series of parametric trajectographic analyses that are carried out on synthetic slopes numerically created with a specifically devoted Matlab code. The slopes are composed of three consecutive ramps with different roles and inclinations (figure 1): i) an initial *detachment zone* with inclination $\omega_1 = 70°$; ii) a following *transit zone* with three possible inclinations: $\omega_2 = 30°, 45°, \text{or } 60°$; iii) a final pseudo-horizontal *stopping zone* with inclination $\omega_3 = 1.5°$. The synthetic slopes were discretized by using a Digital Terrain Model (DTM) with cell size equal to 5 m. A single

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detachment point (corresponding to a single DTM cell) was assumed in the first detachment zone, from which the trajectographic rockfall simulations were performed.

The fully 3D RAMMS::ROCKFALL model was chosen to carry out the simulations because it allows to take into account the real shape of the block introducing sharp and rounded edges with isometric, platy, and elongated shapes [15]. In all the analyses, a given rock density $\rho_r = 2500$ kgm^{-3} was assumed. In the first stage of the work, ground properties were addressed to represent typical alpine slopes. A Medium-Hard soil was assumed in both the detachment and transit zones in order to consider a low-dissipative terrain with small penetration depths (i.e., plastic deformability), flat surface ground, and presence of some rocky debris. Instead, a Medium soil was assumed in the stopping zone, to represent a more plastic and dissipative terrain such as deep meadows containing rock fragments [14]. Finally, no forest coverage was introduced on the entire slope for the purpose of not introducing another important variable in the analyses.

The first set of parametric analyses was referred to cuboid regular shapes (figure 2 a,b,c). To take into account the elongation of the rock block, a slenderness ratio Λ was defined as:

$$\Lambda = \frac{h}{l} \tag{1}$$

where h and l are the main sizes (minimum and maximum) of the block under the assumption that sharp edges and perpendicular faces are considered (figure 2 a,b,c). Three cases might originate depending on the value of Λ: i) platy shape with $\Lambda < 1$; ii) isometric shape (a cube) with $\Lambda = 1$; iii) elongated shape with $\Lambda > 1$. Five values of Λ were assumed in the parametric analysis: 0.25, 0.50, 1.00, 2.00, and 4.00, to take into account a wide range of slenderness variation. With the aim of exploring the effect of block volume, each set of analyses was then repeated simulating blocks of different volume: 0.5, 1, 5, 10 m^3.

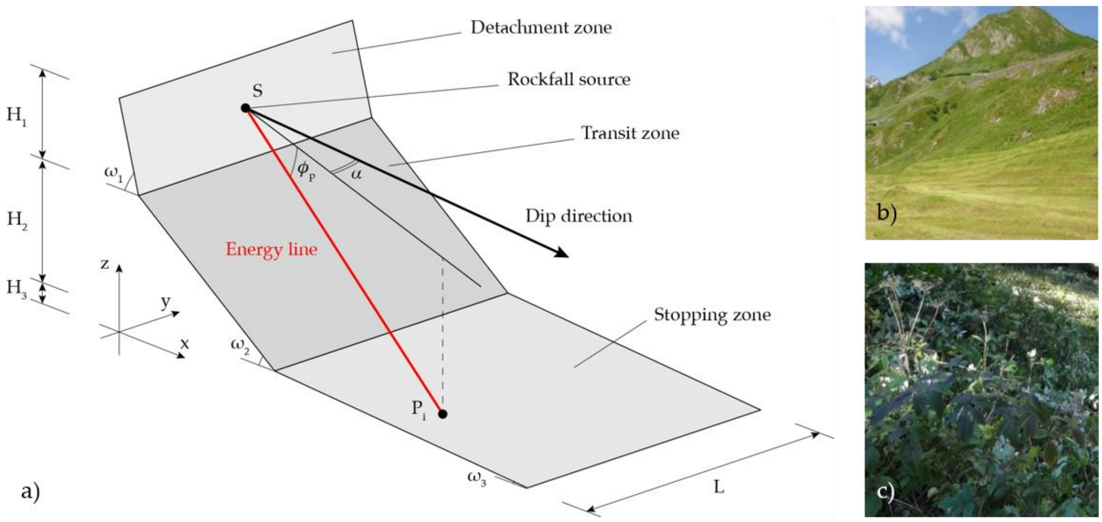

Figure 1. a) Synthetic slope with indication of the three zones. The energy line connects the source point S to the i-th stopping point P_i. The energy angle ϕ_p (defined in the vertical plane) and the lateral angle α (defined by the projection of the energy line on the horizontal plane) are also shown. b) Medium-Hard soil associated to the detachment and transit zone. c) Medium soil associated to the stopping zone [14].

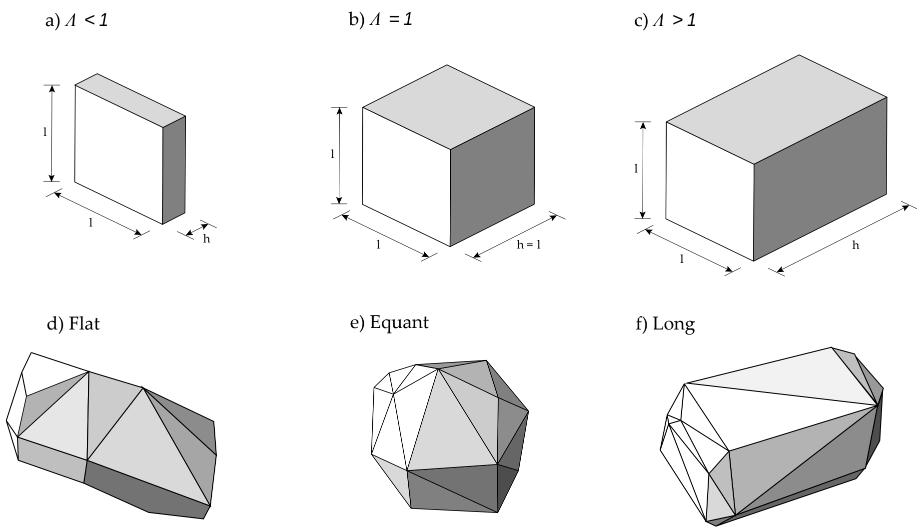

Figure 2. Examples of the block shapes adopted in this work. The first row (a, b, and c) shows regular blocks (cuboids), while the second one (d, e, and f) refers to rounded realistic blocks obtained with the RAMMS *rock builder* tool.

Table 1. Main dimensions of flat, equant, and long realistic blocks, represented in figure 2 d, e, f respectively, with indication of the axial direction (h) and the radial direction (l) and the slenderness value (Λ).

	x (m)	y (m)	z (m)	Λ (-)
Flat 2.0	1.47 (l)	1.32	0.74 (h)	0.5
Equant	1.19	1.19	1.19	1.0
Long 2.0	1.63 (h)	0.98	0.82 (l)	2.0

Finally, with the aim of extending the investigation on the role of block shape on the energy angle, a second set of parametric analyses was carried out with reference to more realistic, rounded and faceted blocks. This can be done through the *rock builder* tool included in RAMMS:: ROCKFALL. Flat, equant and long realistic blocks were therefore considered as shown in figure 2 d,e,f. Block slenderness can again be evaluated through the ratio between block sizes in the axial direction (h) and the radial direction (l). The parametric analyses were then referred to the following shapes: i) flat_2.0 ($l = 2h$, $\Lambda = 0.5$), ii) equant_1.0 ($h = l$, $\Lambda = 1$), and iii) long_2.0 ($h = 2l$, $\Lambda = 2$) (figure 2 d,e,f and table 1). In these simulations it is not possible to consider rocks with $\Lambda = 0.25$ and $\Lambda = 4$ because they are not included into the rock library. Actually, very long and very platy blocks are not highly realistic because of fragmentation and edge smoothing phenomena that occur during the rockfall process. However, in the development of the methodology and in order to highlight the role of slenderness in the behavior of the block, the results of cuboid shapes with very low and very high slenderness were included in the work and are discussed in this paper.

The influence of slope geometry was finally taken into account by considering three different inclinations of the transit zone ω_2: 30°, 45°, and 60°. No variation of slope height was assumed in this phase but an automatic Z offset (i.e. the initial fall height of the rocks measured from the center of mass) was set to impress the minimum offset needed to start the rock motion [14].

2500 trajectories with random orientations were simulated for each combination of parameters to take into account the variability of the phenomenon through a statistical distribution of the results. The output of RAMMS::ROCKFALL mainly consists in a series of raster files showing the spatial distribution of several results, such as block velocity, kinetic energy, stopping points etc. On the basis of the DTM and the distribution of stopping points (deposition map), a Matlab script allowed to compute the energy angle ϕ_p of all the 2500 simulated trajectories as follows (figure 1):

$$\phi_{p,i} = tan^{-1}\frac{z_s - z_{pi}}{\sqrt{\left(x_s - x_{pi}\right)^2 + \left(y_s - y_{pi}\right)^2}} \tag{2}$$

where S is the rockfall source and P_i is the i-th stopping point.

As an example, figure 3 shows the deposition map, the frequency distribution of the energy angle and the cumulative distribution functions (CDFs, hereafter) resulting from a typical analysis.

Since representative angles should be conservative, i.e., should be related to the maximum possible extension of the invasion zone, the 2nd percentile ($\phi_{p,2\%}$) was selected as representative of the whole CDF. This means that 98% of the simulated trajectories are included in a cone with inclination in the vertical plane equal to $\phi_{p,2\%}$, as shown in figure 3. In the following, all the findings will be described in terms of 2nd percentile of the energy angle, so the notation is simplified as follows: $\phi_{p,2\%} = \phi_p$.

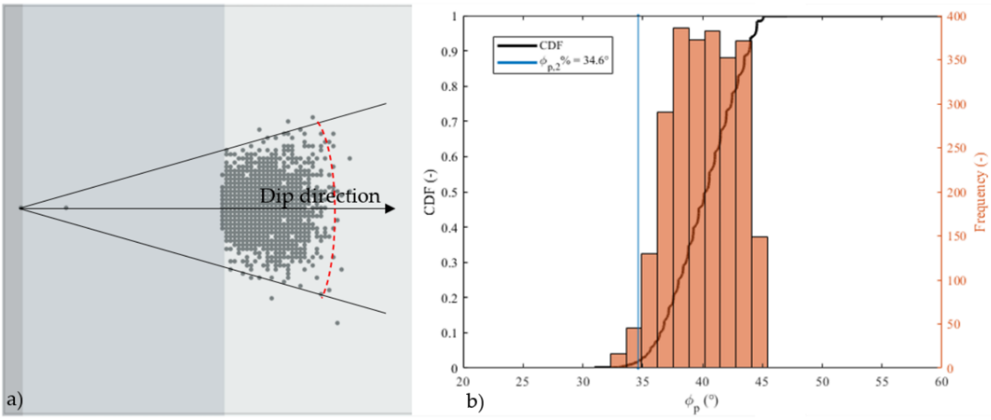

Figure 3. a) Example of deposition map with indication of the cone covering 98% of the stopping points, obtained with $\phi_{p,2\%}$ in the case of 1 m^3 block, $\Lambda = 1$ slenderness, and $\omega_2 = 45°$. b) Frequency distribution and Cumulative Distribution Function (CDF) of the energy angle with indication of the reference value $\phi_{p,2\%}$

3. Result

3.1. Cuboids

The results of the parametric analyses carried out on cuboids are reported in figure 4 using a boxplot representation in the $\Lambda - \phi_p$ plane and in table 2 with reference to the 25th, 50th, 75th percentiles. The following main observation can be done:

- The energy angle globally increases when slope inclination rises.
- The variation trend of the energy angle with reference to block slenderness is similar on slopes of different inclination. The trend shows a minimum for $\Lambda = 1$ (cubic blocks) and higher energy angle values are obtained for $\Lambda \neq 1$. This means that cubic blocks produce wider invasion areas than platy or elongated blocks.
- The effect of block volume is to produce a dispersion of the results within a certain scenario (i.e., given slope inclination and block slenderness) without modifying the above-described general trend (figure 4). This variability however seems to have no correlation with the variables considered here and can be at the moment be considered as uncertainty. For this

reason, energy angle values are reported in table 2 with reference to the 25th percentile, 50th percentile and 75th percentile.

The latter aspect needs however some more detailed analyses and can be due to the calibration of ground properties considered by RAMMS:ROCKFALL, that could be less reliable when small volumes are simulated ($V < 1$ m^3).

Table 2. Energy angle values obtained from the analyses with reference to the 25th, 50th, 75th percentiles (left, middle and right respectively).

	$\Lambda = 0.25$	$\Lambda = 0.5$	$\Lambda = 1$	$\Lambda = 2$	$\Lambda = 4$
ω_2 (°)	ϕ_p (°)	ϕ_p (°)	ϕ_p (°)	ϕ_p (°)	ϕ_p (°)
30	37.5 , 39 , 40.5	32.5 , 33 , 33.5	27 , 28 , 29	34.5 , 35 , 36.5	35 , 35 , 35.5
45	43.5 , 44 , 44	38.5 , 39 , 39	34 , 35 , 35.5	38 , 39 , 40	41 , 41.5 , 42
60	54 , 54 , 54	48.5 , 49 , 49.5	43 , 44.5 , 45	49 , 50.5 , 51.5	52 , 53.5 , 54.5

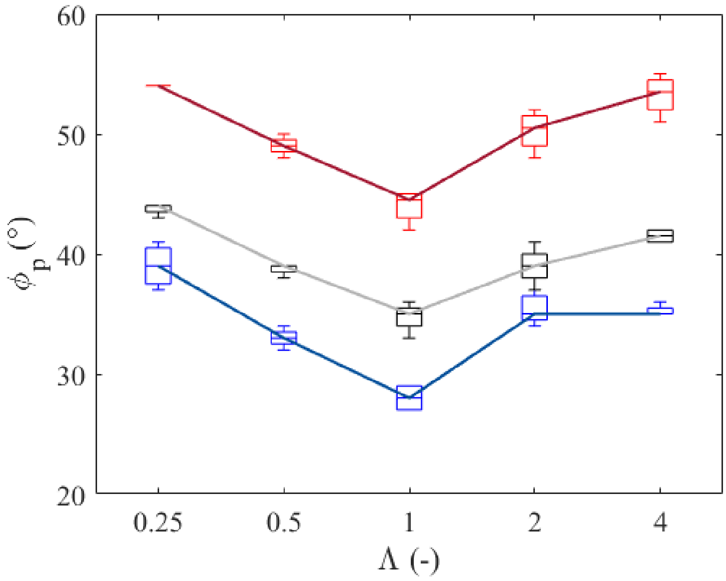

Figure 4. Boxplots displaying the variability of the energy angle as a function of block slenderness: blue is referred to $\omega_2 = 30°$, black to $\omega_2 = 45°$ and red to $\omega_2 = 60°$. Each line connects the median of a group of value.

3.2. *Realistic shapes*

To compare the behavior of cuboids (regular shape) to that of realistic, irregular blocks, the RAMM::ROCKFALL tool *rock builder* was used, which allows to set realistic block geometries. For sake of simplicity, we firstly referred to a block with volume 1 m^3 slopes with inclination 30°, 45° and 60°. The variability produced by a variation of block volume will be investigated in future insights.

Equant, flat 2.0 and long 2.0 block shapes where considered, whose main dimensions are reported in table 1. The results show that realistic blocks have the same tendency of cuboids: equant, isometric blocks reach greater distances than flat and long ones. The effect of slenderness on the energy angle is similar to that of cuboids: increasing Λ up to 1 means a decrease of ϕ_p, while an increase of Λ starting from 1 involves an increase of ϕ_p. However, the general trend is that cuboids run minor runout distances than realistic shape blocks and the major variation is for 30° slope angle and $\Lambda \neq 1$, as reported in figure 5.

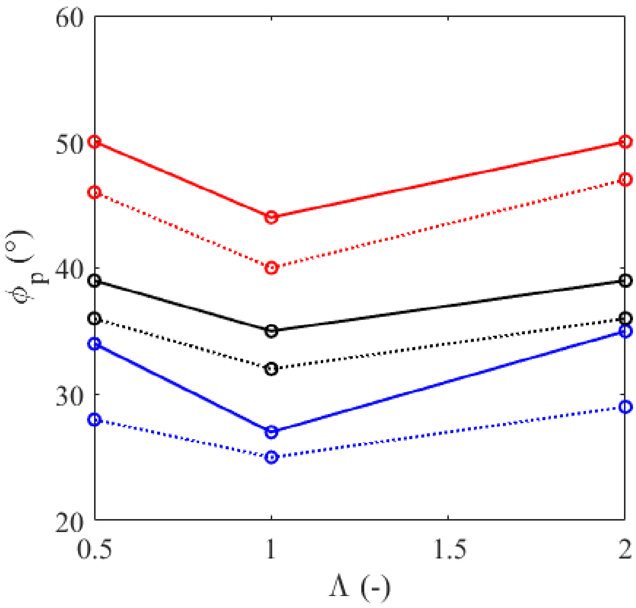

Figure 5. Results of the comparison between cuboids (solid lines) and realistic blocks (dotted lines): blue is referred to $\omega_2 = 30°$, black to $\omega_2 = 45°$ and red to $\omega_2 = 60°$.

4. Discussion and Conclusions

The work presented here is part of a wider study which is devoted to the definition of the factors affecting rockfall phenomena and their simplified representation through the energy angle. Such angle is the main input parameter in the Cone Method, used within the QGIS plugin QPROTO for preliminary hazard analyses at a medium-small scales, and needs to be estimated with reference to the scenario under study (slope characteristics, block characteristics). The final aim of the study is thus to provide the QPROTO users with a tool for the estimation of the energy angle as a function of the main factors that influence this natural slope instability phenomenon.

The methodology of work is based on a wide number of detailed trajectographic analyses carried out on simplified synthetic slopes that are performed through a parametric variation of the main factors influencing the phenomenon, and a statistical analysis of the results to obtain a representative value of the energy angle for each combination of parameters.

In this paper, the effect of block shape and slenderness is investigated. To this aim, we used the 3D rigid body software RAMMS::ROCKFALL to perform the trajectographic analyses, since it allows to simulate real block shapes and to assess their effect on the evolution of the rockfall event. Two series of analyses were then carried out with a parametric variation of slope inclination, block slenderness, and block volume, with reference to regular blocks (cuboids) and faceted (realistic) blocks.

The findings are consistent with both literature references and in situ observations [4,5,15]: isometric blocks run greater distances than slender or platy (flat) blocks. This effect is observed in both cuboids and realistic blocks and leads to the minimum value of the energy angle. With increasing or decreasing block slenderness the runout distance decreases and the energy angle increases. This means that disregarding block slenderness in preliminary simplified analyses is a conservative assumption. On the contrary, considering regular block shapes seems not conservative, since cuboids show minor energy angles than realistic-shaped blocks. This could be due to the effect of friction that regulates the behavior of the blocks in contact with the ground. This hypothesis will be investigated in future developments of this research in order to define a correlation between the energy angle and a sort of "degree of regularity" of block shape. Finally, the variation of the block volume, investigated here with reference to cuboids only, produces a variability in the results that does not seem correlated to other factors. Again, this aspect should be deepened in the future with reference to irregular shapes as well.

Some other factors that have a strong influence on rockfall analyses have been disregarded in this paper, such as the length of the slope, the soil type, and the presence of trees or other obstacles. They will be included in the methodology in the future, to improve the contribution of the research in the comprehension of rockfall phenomena and their simplified representation at medium-small scales, and to provide some indication to QPROTO users for the estimation of parameters in preliminary rockfall analyses.

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