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# Rockfall hazard analysis at small scale: a numerical study for the estimation of representative slope parameters

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**Abstract** The identification of rockfall-affected areas depends on a large number of stochastic variables influencing both triggering and propagation phases. Rockfall hazard assessment presents huge uncertainties linked to the various scales of analysis: at the small scale (e.g. valley scale), a quick evaluation of rockfall hazard zones is generally required in order to highlight the most critical situations where more detailed analyses should be carried out. The Cone Method (Jaboyedoff and Labiouse, 2011), recently implemented by Castelli et al. (2019) in the QPROTO plugin for QGIS, allows to reach this goal with simplified geometrical considerations. In a 3D analysis, the energy line angle  $\varphi_p$  and the lateral spreading angle  $\alpha$  define a cone of propagation whose apex is located in the rockfall source point. The most significant problem in using the plugin is the evaluation of this angles, which must be defined by the users to consider all the rockfall dissipative processes included in the energy line method (Evans and Hungr, 1993). In this paper a study concerning the influence of slope properties (i.e., forest coverage, inclination) and block characteristics (i.e., shape, volume) is proposed, in order to provide to the users of the plugin a preliminary dataset of calibrated angles.

**Keywords:** rockfall, hazard analysis, cone method, QGIS, QPROTO.

## 1 Introduction

Rockfalls are dangerous and widespread phenomena that can affect both natural and artificial slopes inducing damages on structure, infrastructure, economical activities and also killing people. The phenomenon starts with the detachment of a single block or a rocky cluster and can be characterized by large volumes, different block shape and high velocities (Rochet, 1987). Blocks, during their descent paths along the slope, can follow different types of movement such as sliding, rolling, bouncing and free-falling (Varnes, 1978). The complexity of the rockfall can be summarized into two main issues: i) difficulties in providing an exhaustive picture of the landslide causes and the consequent relationships between causes and their effects (i.e., temporal variability of the rockfall magnitude), and ii) modeling the runout phase to provide a spatial description of the expected rockfall scenarios in terms of intensity of the phenomenon (i.e., kinetic energy

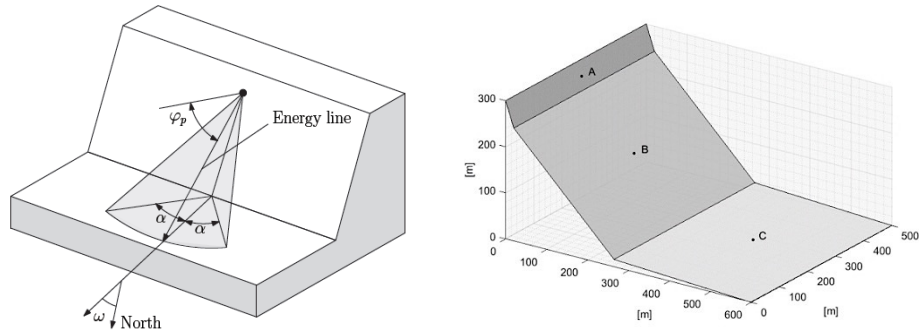
38 content). Over the years, a considerable number of methodologies, correlations and soft-  
39 ware have been developed in order to provide more detailed procedures for the hazard  
40 estimation, also with the aim of on-site and laboratory tests. Moreover, by using either  
41 qualitative or quantitative methodologies, it is possible to assess the vulnerability of the  
42 elements at risk within rockfall-prone areas for providing an estimation of the risk level,  
43 in space and time components (Fell, 2005).

44 Within the wide set of methods for estimating the extent of rockfall-exposed zones, the  
45 simplest ones are the empirical ones. For example, a simple 2D procedure to define the  
46 runout area is the *fahrböschung approach* proposed by Heim (1932). This method relates  
47 the horizontal length of the runout zone to the vertical height of the affected area by  
48 defining an angle  $\beta$  that allows to identify the maximum distance travelled by falling  
49 blocks. In 1993, the *fahrböschung* method was modified by Evans and Hungr (1993) in  
50 the shadow angle one, by referring not to the source point but to the apex of the talus  
51 slope in order to overcome the difficulties in determining the exact location of the source  
52 point. Following the Heim's theory, Onofri and Candian theorized the cone method that  
53 allows to evaluate the maximum distance covered by a block starting from the detach-  
54 ment point (Onofri and Candian, 1979). The methodology was implemented by Ja-  
55 boyedoff and Labiouse (2011) in the CONEFALL software. The basic idea is the concep-  
56 t of the energy line that is empirically defined in the vertical plane by the straight  
57 line connecting the source point with the farthest block stopping point. The inclination  
58 of the energy line with respect to the horizontal, defines the angle  $\varphi_p$  that represents all  
59 the energy losses suffered by the rock block along its descent path. The complex runout  
60 phase can be thought as an equivalent sliding process along the energy line, in which  
61 the  $\varphi_p$  angle assumes the meaning of an equivalent friction angle block-slope.

62 The cone method was recently implemented in the QPROTO plugin, developed for  
63 QGIS 3.4 environment by Castelli et al. (2019). QPROTO allows to identify the inva-  
64 sion area and to estimate the susceptibility and the time-independent (i.e. relative) haz-  
65 ard given by a rockfall phenomenon, by conducting a viewshed analysis of the cliff. The  
66 viewed areas represent the zones in which rockfall events could occur. Starting from a  
67 set of predefined source points, the plugin computes as much visibility cones by adopt-  
68 ing only two input parameters: the energy line angle  $\varphi_p$  and the lateral spreading angle  
69  $\alpha$  that define the cone in the vertical and horizontal planes, respectively. The vertical  
70 distance between the energy line and the topographical surface gives a measure of the  
71 kinetic energy of the block in each point of the invasion zone (Fig. 1a).

72 Nowadays, the values of the cone method angles can be found through empirical meth-  
73 ods available in literature which have a limited application field (Fratini et al., 2012)  
74 restricted to cases where a detailed knowledge of all the parameters and boundary con-  
75 ditions affecting a rockfall phenomenon (i.e. slope geometry, material properties, pres-  
76 ence of vegetation, protection structures etc.) is available. Thus, the aim of the present  
77 paper is to provide to QPROTO users a set of usable values for  $\varphi_p$  and  $\alpha$  angles to carry  
78 on reliable rockfall simulations. Therefore, a set of parametric analyses was carried out  
79 through the software Rockyfor3D which allows to take into account a relevant number  
80 of block and slope features (vegetation, volume and shape of the blocks) and also to  
81 measure the energy line angle of the simulated trajectories (Dorren, 2015).

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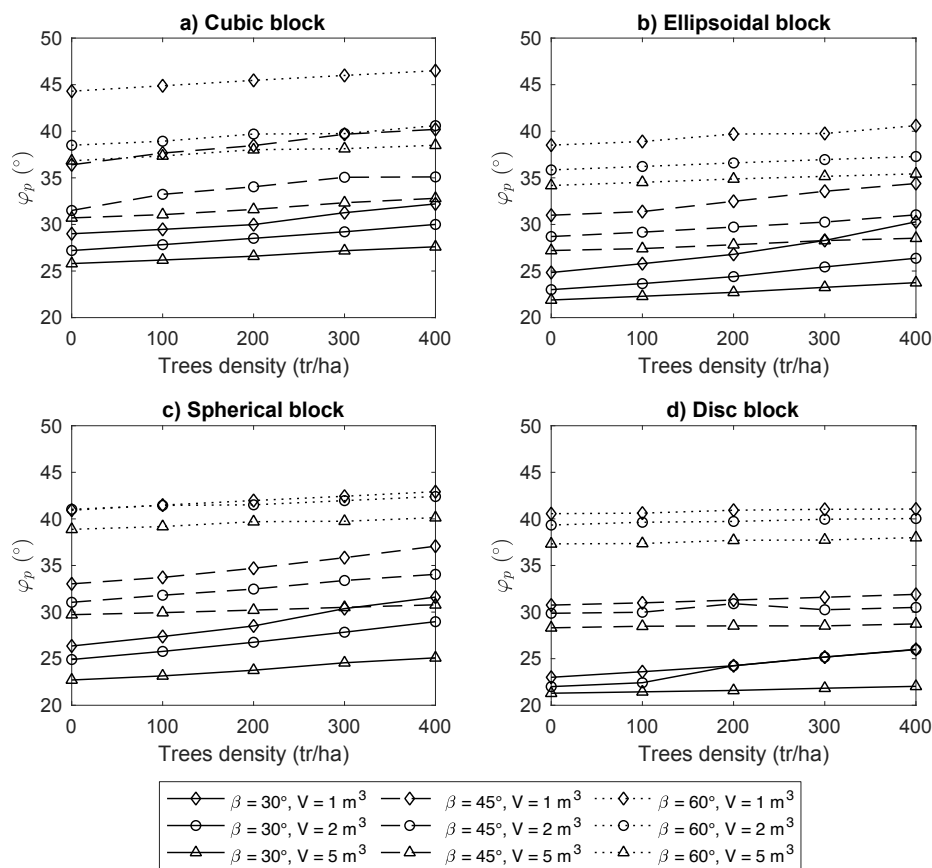
84 **Fig. 1** a) Representation of the parameters characterizing the cone method: the visibility cone is completely  
 85 defined by the vertical angle  $\varphi_p$  and the horizontal angle, while the orientation is given by the  
 86 aspect of the slope evaluated in the source point. b) Geometry of the synthetic slope: detachment zone  
 87 (A), runout zone (B) and stopping zone (C).

## 88 2 Estimation of the input parameters for QPROTO plugin

89 QPROTO is a simplified tool for assessing the rockfall hazard. Its simplicity is linked  
 90 to the few parameters required for carrying on its analyses. In particular, the  $\varphi_p$  angle is  
 91 still a mechanical parameter including in its value all the variables that can potentially  
 92 influence a rockfall process, i.e., morphological characteristics of the slope (steepness,  
 93 length, trees density, roughness, presence of protection works, etc.) and rock block fea-  
 94 tures (volume and size). In order to relate the above-mentioned elements to the corre-  
 95 sponding  $\varphi_p$  values, a set of trajectographic analyses have been performed using the  
 96 rigid body 3D probabilistic method implemented into the software Rockyfor3D (Dorren,  
 97 2015). The analyses were carried out through the synthetic slopes which are obtained  
 98 from the union of three planar surfaces (Fig. 1b): detachment zone (A), runout zone (B)  
 99 and stopping zone (C) (Netti et al., 2016). The slopes have been generated using a con-  
 100 stant value of the height, a different value of the inclination angle  $\beta$  (i.e., the inclination  
 101 of the line connecting the source point with the cliff foot,  $\beta$ :  $30^\circ$ ,  $45^\circ$ ,  $60^\circ$ ) and a semi-  
 102 flat stopping area with an inclination of about  $2^\circ$ . In order to obtain comparable results,  
 103 the morphological characteristics of the slopes are the same; the soil type used in the  
 104 simulations is talus slope or compact soil with large rock fragments for both the detach-  
 105 ment and runout zones (A and B) and fine soil material for the stopping zone (C)  
 106 (Dorren, 2015).

107 Therefore, slopes are discretized by using Digital Terrain Model (DTM, hereafter) with  
 108 cell size of 5 m: the source area is a single DTM cell with four different shapes (i.e.,  
 109 cubic, ellipsoidal, spherical and disc), three different volumes (i.e.,  $1 \text{ m}^3$ ,  $2 \text{ m}^3$ ,  $5 \text{ m}^3$ )

110 and a constant rock density of  $2500 \text{ kg/m}^3$ . Rockyfor3D allows to take into account the  
 111 effect of trees on the trajectories. Thus, five levels of vegetation density were consid-  
 112 ered: 0, 100, 200, 300 and 400 trees/ha (i.e., 1 tree/DTM cell). Trees were placed only  
 113 in the runout area and their essence was set 100% conifers, considering their least mech-  
 114 anical resistance to rockfall impacts (Stokes et al. 2005, Dorren and Berger, 2005). A  
 115 value of 35 cm for the breast-height diameter (DBH) was finally established.  
 116 A total number of 20000 simulated trajectories for each combination of parameters was  
 117 conducted and the final energy line angle was defined as the 2% ( $\varphi_{p,2\%}$ ) of the empirical  
 118 distribution function (EDF) i.e., the angle value that have the 98% of probability to be  
 119 maximized. It is obvious that smaller angles relate to wider runout area and thus precau-  
 120 tionary values have to be considered.



121

122 **Fig. 2** Energy line angle values sorted with reference to the block shape. a) Cubic shape gives the higher  
 123 values of  $\varphi_p$ . b) and c) are related to ellipsoidal and spherical blocks, respectively. It can be seen that  
 124 the corresponding angle are generally lower in this case because of the higher rotational inertia of these  
 125 shapes. d) In disc shape case the minimum angles are obtained.

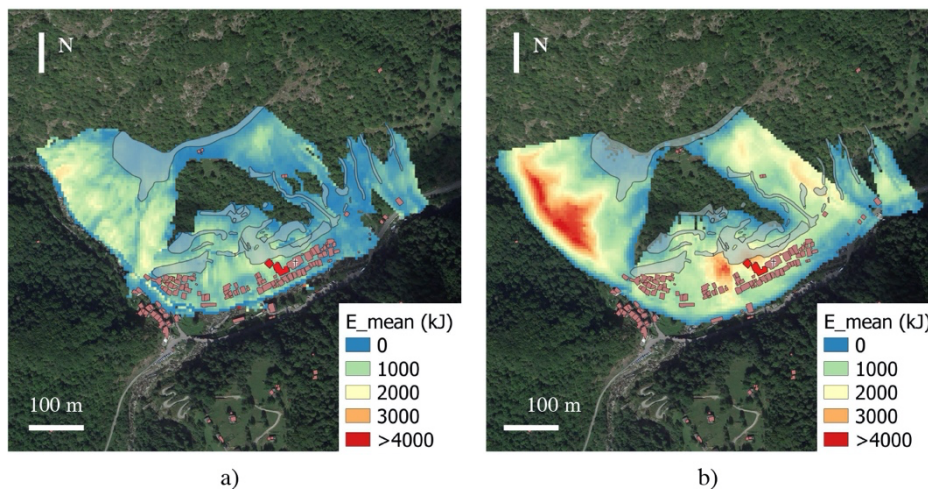
126 In order to analyze the results obtained from the synthetic slopes (Fig. 2) and to highlight  
127 the most relevant aspects, it is possible to observe that a considerable increase of  $\varphi_p$   
128 angles is linked to the growing of the slope steepness (i.e., the  $\beta$  angle). This growing  
129 is more relevant for smaller volumes while 5 m<sup>3</sup> blocks have smaller energy line angles.  
130 Limited slope steepness increases the rolling of the blocks also in the stopping zone of  
131 the synthetic cliff, decreasing the corresponding energy line angles. The density of trees  
132 increases the  $\varphi_p$  angles with a maximum difference of about 5°, especially in case of  
133 cubic, ellipsoidal and spherical shapes. The disc shape is less influenced by the forest  
134 because of its highest rotational inertia that provides longer descent paths to blocks. 5  
135 m<sup>3</sup> blocks are minimally influenced by trees allowing to conclude that this volume is the  
136 maximum limit for trees to still play a protective role against rockfalls (Torsello, 2019).  
137 The influence of shape is highly clear: cubic blocks give maximum energy angles while  
138 minimum ones are due to disc shaped boulders.  
139 Highest values of energy line angle can be found for a volume of 1 m<sup>3</sup> and  $\beta$  angle of  
140 30° for cubic, ellipsoidal and spherical blocks while smaller values can be found for disk  
141 shaped blocks. A lower value of energy line angle  $\varphi_p$  corresponds to greater runout  
142 lengths and to greater kinetic energies with a minor capacity to stop or decelerate blocks  
143 by trees, according with the case study reported in Kobayashi et al. (1990) in which a  
144 disk-shaped block smashed trees up to 0.6 m and followed a total horizontal travel dis-  
145 tance of about 420 m.

### 146 **3 Case study: the Rassa site**

147 In order to test the reliability of the above described results, an application to a real case  
148 study is reported in the following. The investigated area belongs to Rassa municipality,  
149 which is located in the Sesia Valley, Western Italian Alps, at an altitude of 917 m a.s.l.  
150 (UTM: 423539, 5068593, 32, T). Rassa is composed by four main hamlets: Bunadaccia-  
151 Scarpie at West, San Giovanni-Concentrico at South, Torbe-Orello at Est and Piana  
152 Giacchè at North. The inhabited area of San Giovanni-Concentrico is located nearby the  
153 confluence of Gronda and Sorba creeks, at the basis of a steep slope that reaches a max-  
154 imum altitude of about 1100 m a.s.l. The cliff is covered by a sparse mixed broad-leaved  
155 forest. Different landslides phenomena have been affected the whole studied area: the  
156 last rockfall event occurred after a huge rainfall event in October 2018, when a 0.1 m<sup>3</sup>  
157 block reached the San Giovanni church without causing damages. In order to calibrate  
158 the parameters, a back analysis of the 2018 event was performed, using Rockyfor3D  
159 and adopting the DTM (5 x 5 m) provided by the Piedmont Region. The energy line  
160 angle  $\varphi_p$  was estimated starting by this analysis and a value of 43° was found. This  
161 value was therefore used within the QPROTO plugin as the input parameter to replicate  
162 the October 2018 event.

163 Then, a forecasting set of analyses for the Rassa site was performed in order to estimate  
164 the hazard level of the area. From geo-structural surveys of the rock face it has been  
165 shown that the maximum magnitude scenario was related to a volume of 5 m<sup>3</sup>.

166 Therefore, a forecasting Rockyfor3D simulation was carried out with reference to this  
 167 volume scenario (Fig. 3a). The analysis was computed by adopting a cubic block shape  
 168 and a trees density of 400 trees/ha, evaluated on the basis of an on-site survey of the  
 169 Rassa forest. The rockfall detachment niches were identified with the most fractured  
 170 portion of the rock face. In order to test the reliability of the angle abacus described in  
 171 this paper, a QPROTO simulation of the 5 m<sup>3</sup> scenario was carried out. The energy line  
 172 angle  $\varphi_p$  was 33°, obtained in correspondence of a trees density of 400 tree/ha, a cubic  
 173 block shape and a slope angle of 45° (Fig. 2a). The results are reported in Fig. 3b. It can  
 174 be seen that the QPROTO and Rockyfor3D invasion areas are the same while QPROTO  
 175 kinetic energy values are higher than Rockyfor3D ones, especially in the Western por-  
 176 tion of the area. This is due to the different starting hypotheses characterizing the two  
 177 approaches. The quick nature of the cone method has to provide precautionary results  
 178 able to highlight the zones in which most in-depth analyses should be carried on.



179 a) b)  
 180 **Fig. 3** Output of the two forecasting analysis for the 5 m<sup>3</sup> scenario. The light grey area relates to the  
 181 rockfall source zones characterized by the fractured rock face, the light red rectangles highlights the  
 182 Rassa village while the red buildings are the structures interested by the 2018 event: a) Rockyfor3D  
 183 simulation, b) QPROTO simulation.

#### 184 4 Conclusions

185 In this paper the preliminary results of the calibration activity of energy line angles for  
 186 cone method are reported. This work assumes a crucial importance in order to provide  
 187 usable and reliable input data for carrying on quick hazard analysis by adopting the cone  
 188 method and, especially, the QPROTO plugin. A series of parametric analyses were car-  
 189 ried out to investigate the possible correlations between  $\varphi_p$  and both block and slope  
 190 characteristics. Referring to the block features, the results show that the influence of the

191 volume and the size are evident. In particular, smaller angles are due to larger volumes  
 192 and disc-shaped boulders. With reference to the slope, the steepness is the key topic and  
 193 largest angles are given by steepest slopes. Also the forest density influences the results:  
 194 smaller volumes (i.e., 1 and 2 m<sup>3</sup>) are associated to the maximum tree effect and the  $\varphi_p$   
 195 grows together with the increase of the density of trees. The lateral spreading angle  $\alpha$   
 196 seems to have a small variability but further studies should be carried out in order to  
 197 investigate the role of this parameter. In this preliminary work we suggest a value of  
 198 lateral spreading angle in a range of  $\pm 20^\circ$  around the dip direction of the slope.  
 199 The results were tested in the case study of Rassa village. It can be seen that the esti-  
 200 mated angles provide precautionary hazard maps with respect to the same ones com-  
 201 puted by using a usual trajectographic software (Rockyfor3D). This is a good issue be-  
 202 cause a quick method, such as QPROTO is, have to be sufficiently precautionary in  
 203 order to supply preliminary rockfall hazard evaluations.  
 204 The above described analyses have been conducted by adopting simplified hypotheses  
 205 such as constant roughness values and absence of rockfall protection works along the  
 206 synthetic slopes. These two aspects can considerably affect the results and further stud-  
 207 ies are ongoing in order to overcome the limit of the present works.

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