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1	Rockfall hazard analysis at small scale: a
2	numerical study for the estimation of
3	representative slope parameters
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10	Abstract The identification of rockfall-affected areas depends on a large number of stochastic
11	variables influencing both triggering and propagation phases. Rockfall hazard assessment presents
12	huge uncertainties linked to the various scales of analysis: at the small scale (e.g. valley scale), a
13	quick evaluation of rockfall hazard zones is generally required in order to highlight the most crit-
14	ical situations where more detailed analyses should be carried out. The Cone Method (Jaboyedoff
15	and Labiouse, 2011), recently implemented by Castelli et al. (2019) in the QPROTO plugin for
16 17	QGIS, allows to reach this goal with simplified geometrical considerations. In a 3D analysis, the energy line angle φ_p and the lateral spreading angle α define a cone of propagation whose apex
18	is located in the rockfall source point. The most significant problem in using the plugin is the
19	evaluation of this angles, which must be defined by the users to consider all the rockfall dissipative
20	processes included in the energy line method (Evans and Hungr, 1993). In this paper a study
21	concerning the influence of slope properties (i.e., forest coverage, inclination) and block charac-
22	teristics (i.e., shape, volume) is proposed, in order to provide to the users of the plugin a prelimi-
23	nary dataset of calibrated angles.
24	
25	Keywords: rockfall, hazard analysis, cone method, QGIS, QPROTO.

26 1 Introduction

27 Rockfalls are dangerous and widespread phenomena that can affect both natural and 28 artificial slopes inducing damages on structure, infrastructure, economical activities and 29 also killing people. The phenomenon starts with the detachment of a single block or a 30 rocky cluster and can be characterized by large volumes, different block shape and high 31 velocities (Rochet, 1987). Blocks, during their descent paths along the slope, can follow 32 different types of movement such as sliding, rolling, bouncing and free-falling (Varnes, 33 1978). The complexity of the rockfall can be summarized into two main issues: i) diffi-34 culties in providing an exhaustive picture of the landslide causes and the consequent 35 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 36 37 expected rockfall scenarios in terms of intensity of the phenomenon (i.e., kinetic energy

content). Over the years, a considerable number of methodologies, correlations and software have been developed in order to provide more detailed procedures for the hazard estimation, also with the aim of on-site and laboratory tests. Moreover, by using either qualitative or quantitative methodologies, it is possible to assess the vulnerability of the elements at risk within rockfall-prone areas for providing an estimation of the risk level, 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 *fahrböscung 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 β that allows to identify the maximum distance travelled by falling 49 blocks. In 1993, the fahrböscung 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 con-56 cept 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 φ_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 φ_p angle assumes the meaning of an equivalent friction angle block-slope.

The cone method was recently implemented in the OPROTO plugin, developed for 62 63 QGIS 3.4 environment by Castelli et al. (2019). QPROTO allows to identify the invasion area and to estimate the susceptibility and the time-independent (i.e. relative) haz-64 65 ard given by a rockfall phenomenon, by conducting a viewshed analysis of the cliff. The viewed areas represent the zones in which rockfall events could occur. Starting from a 66 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 φ_p and the lateral spreading angle 69 α 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 (Frattini 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 φ_p and α 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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Fig. 1 a) Representation of the parameters characterizing the cone method: the visibility cone is completely defined by the vertical angle φ_p and the horizontal angle, while the orientation is given by the aspect of the slope evaluated in the source point. b) Geometry of the synthetic slope: detachment zone (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 φ_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 φ_n 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 β (i.e., the inclination 101 of the line connecting the source point with the cliff foot, β : 30°, 45°, 60°) and a semi-102 flat stopping area with an inclination of about 2°. 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 m³, 2 m³, 5 m³)

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and a constant rock density of 2500 kg/m³. Rockyfor3D allows to take into account the effect of trees on the trajectories. Thus, five levels of vegetation density were considered: 0, 100, 200, 300 and 400 trees/ha (i.e., 1 tree/DTM cell). Trees were placed only in the runout area and their essence was set 100% conifers, considering their least mechanical resistance to rockfall impacts (Stokes et al. 2005, Dorren and Berger, 2005). A 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

122Fig. 2 Energy line angle values sorted with reference to the block shape. a) Cubic shape gives the higher123values of φ_p . b) and c) are related to ellipsoidal and spherical blocks, respectively. It can be seen that124the corresponding angle are generally lower in this case because of the higher rotational inertia of these125shapes. d) In disc shape case the minimum angles are obtained.

In order to analyze the results obtained from the synthetic slopes (Fig. 2) and to highlight 126 127 the most relevant aspects, it is possible to observe that a considerable increase of φ_p 128 angles is linked to the growing of the slope steepness (i.e., the β angle). This growing 129 is more relevant for smaller volumes while 5 m^3 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 φ_p angles with a maximum difference of about 5°, especially in case of cubic, ellipsoidal and spherical shapes. The disc shape is less influenced by the forest 133 134 because of its highest rotational inertia that provides longer descent paths to blocks. 5 m³ blocks are minimally influenced by trees allowing to conclude that this volume is the 135 136 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. Highest values of energy line angle can be found for a volume of 1 m³ and β angle of 139 30° for cubic, ellipsoidal and spherical blocks while smaller values can be found for disk 140 141 shaped blocks. A lower value of energy line angle φ_p corresponds to greater runout 142 lengths and to greater kinetic energies with a minor capacity to stop or decelerate blocks

by trees, according with the case study reported in Kobayashi et al. (1990) in which a 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 m³ 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 φ_p was estimated starting by this analysis and a value of 43° was found. This value was therefore used within the QPROTO plugin as the input parameter to replicate 161 162 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 m³. 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 portion of the rock face. In order to test the reliability of the angle abacus described in 170 this paper, a QPROTO simulation of the 5 m³ scenario was carried out. The energy line 171 172 angle φ_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.





Fig. 3 Output of the two forecasting analysis for the 5 m³ scenario. The light grey area relates to the
 rockfall source zones characterized by the fractured rock face, the light red rectangles highlights the
 Rassa village while the red buildings are the structures interested by the 2018 event: a) Rockyfor3D
 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 φ_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 m³) are associated to the maximum tree effect and the φ_n 195 grows together with the increase of the density of trees. The lateral spreading angle α 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.

The above described analyses have been conducted by adopting simplified hypotheses such as constant roughness values and absence of rockfall protection works along the synthetic slopes. These two aspects can considerably affect the results and further studies are ongoing in order to overcome the limit of the present works.

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