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 φ_p and the lateral spreading angle α 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 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).

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

The cone method was recently implemented in the QPROTO plugin, developed for 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) hazard 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 set of predefined source points, the plugin computes as much visibility cones by adopting only two input parameters: the energy line angle φ_p and the lateral spreading angle α that define the cone in the vertical and horizontal planes, respectively. The vertical distance between the energy line and the topographical surface gives a measure of the kinetic energy of the block in each point of the invasion zone (Fig. 1a).

Nowadays, the values of the cone method angles can be found through empirical methods available in literature which have a limited application field (Frattini et al., 2012) restricted to cases where a detailed knowledge of all the parameters and boundary conditions affecting a rockfall phenomenon (i.e. slope geometry, material properties, presence of vegetation, protection structures etc.) is available. Thus, the aim of the present paper is to provide to QPROTO users a set of usable values for φ_p and α angles to carry on reliable rockfall simulations. Therefore, a set of parametric analyses was carried out through the software Rockyfor3D which allows to take into account a relevant number of block and slope features (vegetation, volume and shape of the blocks) and also to measure the energy line angle of the simulated trajectories (Dorren, 2015).

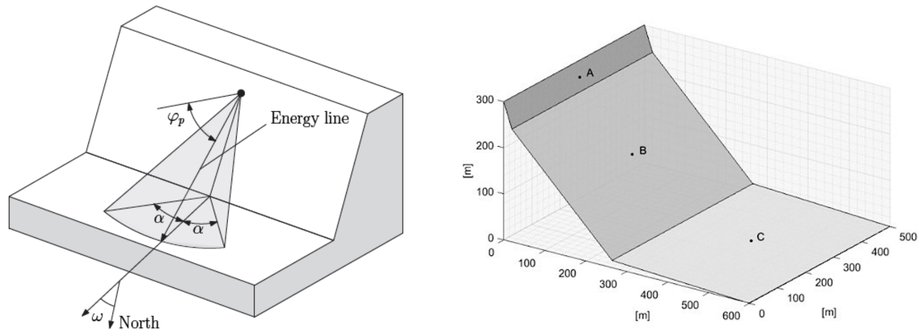


Fig. 1 a) Representation of the parameters characterizing the cone method: the visibility cone is completely defined by the vertical angle φ_p and the horizontal angle, while the orientation is given by the aspect of the slope evaluated in the source point. b) Geometry of the synthetic slope: detachment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

2 Estimation of the input parameters for QPROTO plugin

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

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

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.
A total number of 20000 simulated trajectories for each combination of parameters was conducted and the final energy line angle was defined as the 2% ($\varphi_{p,2\%}$) of the empirical distribution function (EDF) i.e., the angle value that have the 98% of probability to be maximized. It is obvious that smaller angles relate to wider runout area and thus precautionary values have to be considered.

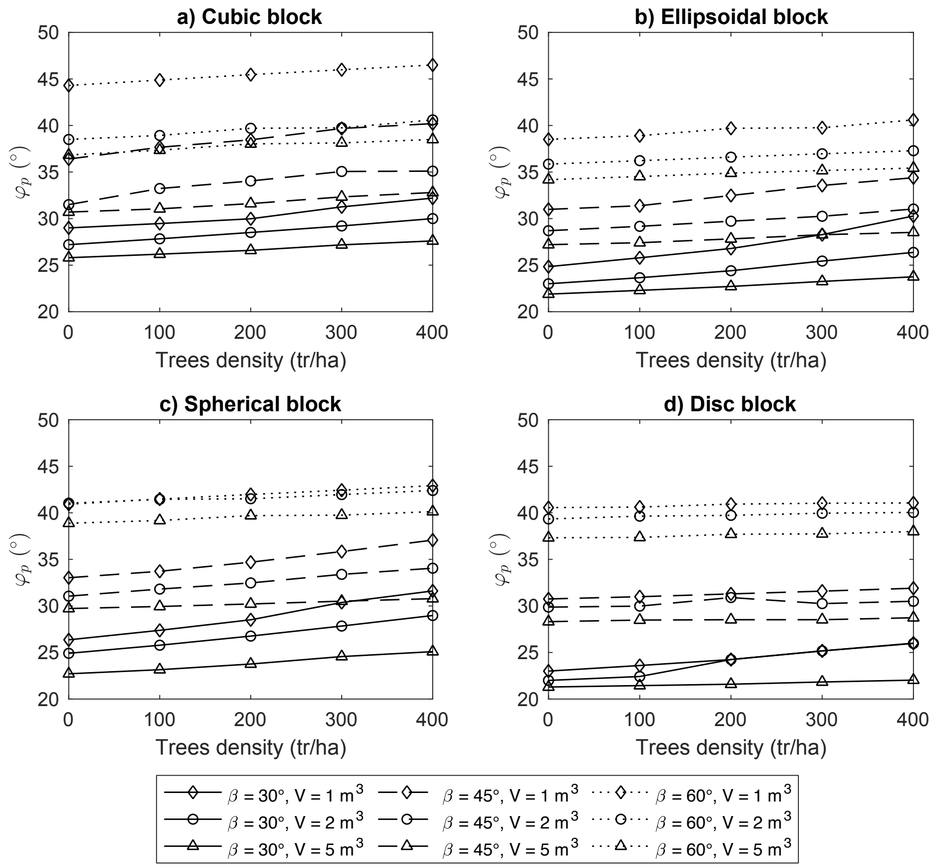


Fig. 2 Energy line angle values sorted with reference to the block shape. a) Cubic shape gives the higher values of φ_p. b) and c) are related to ellipsoidal and spherical blocks, respectively. It can be seen that the corresponding angle are generally lower in this case because of the higher rotational inertia of these shapes. 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 the most relevant aspects, it is possible to observe that a considerable increase of φ_p angles is linked to the growing of the slope steepness (i.e., the β angle). This growing is more relevant for smaller volumes while 5 m^3 blocks have smaller energy line angles. Limited slope steepness increases the rolling of the blocks also in the stopping zone of the synthetic cliff, decreasing the corresponding energy line angles. The density of trees 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 because of its highest rotational inertia that provides longer descent paths to blocks. 5 m^3 blocks are minimally influenced by trees allowing to conclude that this volume is the maximum limit for trees to still play a protective role against rockfalls (Torsello, 2019). The influence of shape is highly clear: cubic blocks give maximum energy angles while minimum ones are due to disc shaped boulders.

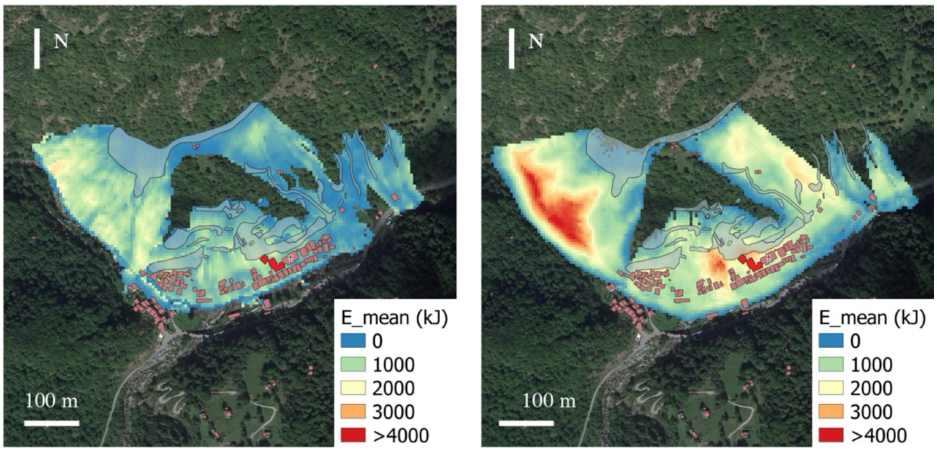
Highest values of energy line angle can be found for a volume of 1 m^3 and β angle of 30° for cubic, ellipsoidal and spherical blocks while smaller values can be found for disk shaped blocks. A lower value of energy line angle φ_p corresponds to greater runout lengths and to greater kinetic energies 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 distance of about 420 m.

3 Case study: the Rassa site

In order to test the reliability of the above described results, an application to a real case study is reported in the following. The investigated area belongs to Rassa municipality, which is located in the Sesia Valley, Western Italian Alps, at an altitude of 917 m a.s.l (UTM: 423539, 5068593, 32, *T*). Rassa is composed by four main hamlets: Bunadaccia-Scarpie at West, San Giovanni-Concentrico at South, Torbe-Orello at Est and Piana Giacchè at North. The inhabited area of San Giovanni-Concentrico is located nearby the confluence of Gronda and Sorba creeks, at the basis of a steep slope that reaches a maximum altitude of about 1100 m a.s.l. The cliff is covered by a sparse mixed broad-leaved forest. Different landslides phenomena have been affected the whole studied area: the last rockfall event occurred after a huge rainfall event in October 2018, when a 0.1 m^3 block reached the San Giovanni church without causing damages. In order to calibrate the parameters, a back analysis of the 2018 event was performed, using Rockyfor3D and adopting the DTM (5 x 5 m) provided by the Piedmont Region. The energy line 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 the October 2018 event.

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

Therefore, a forecasting Rockyfor3D simulation was carried out with reference to this volume scenario (Fig. 3a). The analysis was computed by adopting a cubic block shape and a trees density of 400 trees/ha, evaluated on the basis of an on-site survey of the 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 this paper, a QPROTO simulation of the 5 m^3 scenario was carried out. The energy line angle φ_p was 33°, obtained in correspondence of a trees density of 400 tree/ha, a cubic block shape and a slope angle of 45° (Fig. 2a). The results are reported in Fig. 3b. It can be seen that the QPROTO and Rockyfor3D invasion areas are the same while QPROTO kinetic energy values are higher than Rockyfor3D ones, especially in the Western portion of the area. This is due to the different starting hypotheses characterizing the two approaches. The quick nature of the cone method has to provide precautionary results able to highlight the zones in which most in-depth analyses should be carried on.



a) b)

Fig. 3 Output of the two forecasting analysis for the 5 m^3 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.

4 Conclusions

In this paper the preliminary results of the calibration activity of energy line angles for cone method are reported. This work assumes a crucial importance in order to provide usable and reliable input data for carrying on quick hazard analysis by adopting the cone method and, especially, the QPROTO plugin. A series of parametric analyses were carried out to investigate the possible correlations between φ_p and both block and slope characteristics. Referring to the block features, the results show that the influence of the volume and the size are evident. In particular, smaller angles are due to larger volumes and disc-shaped boulders. With reference to the slope, the steepness is the key topic and largest angles are given by steepest slopes. Also the forest density influences the results: smaller volumes (i.e., 1 and 2 m^3) are associated to the maximum tree effect and the φ_p grows together with the increase of the density of trees. The lateral spreading angle α seems to have a small variability but further studies should be carried out in order to investigate the role of this parameter. In this preliminary work we suggest a value of lateral spreading angle in a range of $\pm 20°$ around the dip direction of the slope.

The results were tested in the case study of Rassa village. It can be seen that the estimated angles provide precautionary hazard maps with respect to the same ones computed by using a usual trajectographic software (Rockyfor3D). This is a good issue because a quick method, such as QPROTO is, have to be sufficiently precautionary in 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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