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Preliminary assessment of rockfall hazard based on GIS data

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GIS documents are of great interest for a quick and low-cost determination of areas endangered by rockfalls. They allow (*i*) the detection of potential instabilities from steep slopes and cliff areas, and (*ii*) the preliminary estimation of potential run-out areas by means of a so-called cone method. After the presentation of the tools used to compute these areas, the paper focuses on two methods developed for a preliminary hazard mapping, one at regional scale and the other at local scale.

Mittels GIS-Dokumenten können von Steinschlag bedrohte Gebiete schnell und kostengünstig ermittelt werden. Die sogenannte Kegelmethode erlaubt die Erkennung potentiell instabiler Zonen von Steilhängen und Felswänden sowie eine erste Einschätzung der möglichen Reichweiten. Nach der Vorstellung der zur Berechnung der bedrohten Gebiete benötigten Hilfsmittel stellt der Artikel zwei Methoden zur vorläufigen Gefahrenkartierung in lokalem und regionalem Maßstab vor.

Les SIG sont très intéressants pour une détermination rapide et peu onéreuse des zones affectées par des chutes de blocs. Ils permettent une détection des zones potentiellement instables et une estimation sommaire des zones de propagation des blocs par une méthode dite des cônes. Après la description des outils utilisés pour définir ces zones, l'article expose deux méthodologies élaborées pour un zonage préliminaire du danger, l'une à l'échelle régionale et l'autre à l'échelle locale.

Introduction

Authorities of mountainous regions often need a quick and low-cost determination of areas endangered by rockfalls. The objectives of this first rough delineation are the early detection of conflicts between land use and rockfall hazard and consequently the identification of zones of the territory where detailed and expensive investigations are required.

Nowadays the increasing availability of geographic information system (GIS) data, such as digital elevation model (DEM), topographic vector map, etc. makes the analyses on large areas easier and cheaper using simple models.

Rockfall Fahrböschung and shadow angle

For the preliminary estimation of maximum rockfall reach, several authors (Heim, 1932; Scheidegger, 1973; Onofri & Candian, 1979; Evans & Hungr, 1993) suggest a simple approach that models rockfalls as the sliding or rolling of a mass on a sloping surface with an average friction angle φ_p (Fig. 1). From energy considerations, this means that a block starting from a source will travel down the slope and stop at the intersection point of the topography with a so-called energy line drawn from the source point and making an angle φ_p with horizontal. An alternative approach uses a shadow angle keyed to the apex of the talus slope (Fig. 2). It assumes that the kinetic energy acquired in the initial fall is largely lost in the first impacts near the top of the slope.

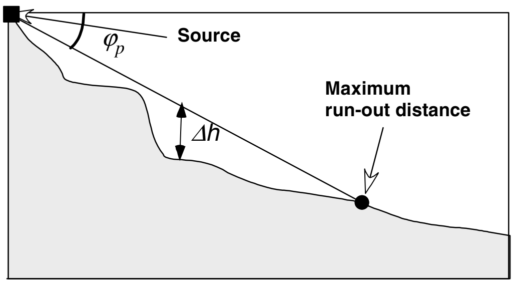

Figure 1: Relationship between φ_p and the maximum run-out distance. Δh is used for the energy estimation.

GIS based cone method

Detection of potential rock instabilities

The determination of potentially unstable rock areas (block sources) depends on the available data and documents: field observations, register of events, air photographs, geological and topographic maps. When GIS data are available, as it is the case in Switzerland, a quick and preliminary delineation of potential instabilities is possible, for instance from the DTM and from the 1:25'000 topographic vector map. The steep slopes (e.g. >45°) computed from the former data and the polygons identified as cliff areas in the latter are merged into one instability grid file in Boolean format, using -1 for no instability and 1 for potential instability.

Assessment of potential run-out distance

The above-presented method for the preliminary estimation of rockfall run-out can be easily generalised to 3D: a rock fragment detaching from a source point can reach any point of the topography located within a vertical cone of slope φ_p (or aperture 90°- φ_p) centred on the source point (or on the bottom of the cliff for the alternative approach). In a DEM, this is simply computed using the relationship:

$$0 < \Delta x^2 + \Delta y^2 - \left(tg(\pi/2 - \phi_p)\right)^2 \times (z_0 - z)^2$$

with the condition z < h and where Δx et Δy are the horizontal distances between the source point and a point tested, z_0 the elevation of the source point and z the elevation of the tested point.

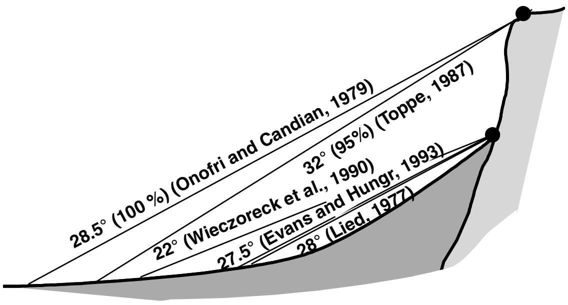

Figure 2: φ_p values from the top or the bottom of a cliff (mod. after Jaboyedoff and Labiouse; Crosta et al., 2001)

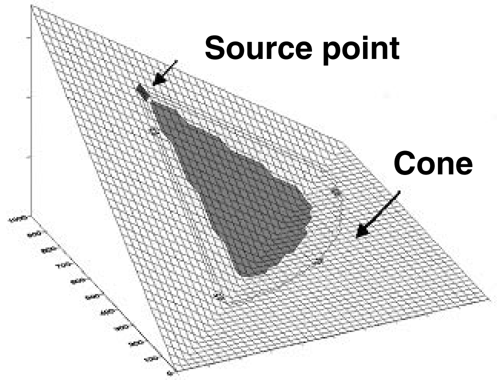

Figure 3: Illustration of the areas endangered by rockfalls starting from a source point, using cone slopes of 35° and 40° (After CONEFALL User's guide).

Each point of the instability grid determined in the first methodology step as potential block source is successively taken as the apex of a vertical cone of (90°- φ_p) aperture. The contouring of all the defined points allows to determine the extent of the areas endangered by rockfalls. The results can be either Boolean values (-1 for not reachable and 1 for reachable) or the sum of the contributing source points. The latter is a crude image of the most probable rockfall paths.
Analyses performed with this cone method are found useful for the preliminary estimation of rockfall reach, provided that the aperture angle is correctly assessed (Figure 2). It is found nevertheless that the method generally overestimates (*i*) the lateral extent of the zones that can be reached by boulders, and (ii) the run-out distance for sites with a near-vertical source standing above a flat relief.

Assessment of velocity and energy

From the difference in elevation Δh between the cone (energy line of Figure 1) and the topography, one can get an estimation of the block velocity as:

$$v_{trans} = f_v \sqrt{2\, g\, \Delta h}$$

where v_{trans} is the translation velocity, g the terrestrial acceleration, and f_v a factor introduced to take into account the rotational kinetic energy (e.g. f_v =0.9). In the same way, if the mass m of the block is fixed, one can assess the total kinetic energy as:

$$E = m\ g\ \Delta h$$

As the cone method assumes a constant energy loss along the topography (slope tg(φ_p) of the energy line), which does not simulate correctly the energy losses of blocks moving down slopes (combination of free flight, bouncing, rolling and sliding), it is essential to interpret those velocity and energy results with great caution.

The software CONEFALL

CONEFALL is a freeware available on www.quanterra.org that simulates the above-explained cone method. It allows the computation of the run-out areas, the number of contributing source pixels, the velocities and kinetic energies. A lateral limitation of the cones is implemented.
The program uses text grid files for the DEM and for the source points. As a special routine has been implemented to extract from a cliff area the bottom pixels, the source points can be either the entire cliff areas or only their bottom as proposed by Evans and Hungr (1993).

Preliminary hazard mapping at regional scale

A preliminary map of rockfall-prone areas of the canton de Vaud in Switzerland (3212 km^2) has been established using the cone method with φ_p = 33° (project CADANAV). The potential block sources were defined by merging the slopes steeper than 40° (computed from the DTM) and the cliff areas available from the 1:25'000 topographic vector map.
Comparison of the results with known events indicated a good agreement between model (Figure 4) and observation.
The objectives of this preliminary hazard map were the early detection of conflicts with land-use planning and the identification, from a simple risk analysis, of the zones where more detailed investigations are first required.

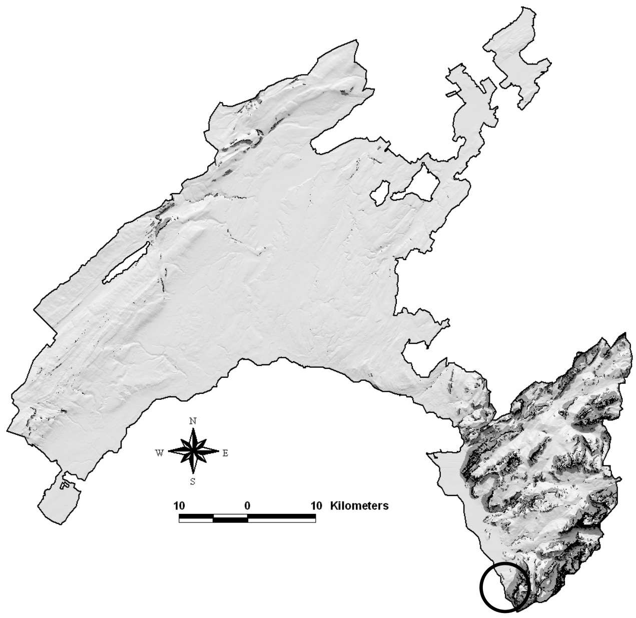

Figure 4: Preliminary map for rockfall-prone areas of the canton de Vaud (CH) superimposed to a shade relief. In dark grey the potential run-out and in black the source areas. The circle indicates the location of Lavey Village.

Preliminary hazard mapping at local scale

Principle of preliminary mapping

Although the methodology used to identify rockfall hazards at local scale (valley or catchment) is rather similar than the regional scale one, there are nevertheless some differences:

- the potential instabilities are subdivided in several zones of similar failure mechanism (plane or wedge slide, toppling, overhang…) and same rock formation. Each of these homogeneous areas is then mapped separately.
- The apexes used for the computation of the cones at regional scale are, for conservative reasons, all the pixels identified as potential block sources (entire cliff areas and slopes steeper than 40°). On the other hand, at local scale, the apexes considered can be either the entire cliff areas or only their bottom, depending on the morphological characteristics of the sites. If GIS data on cliffs are not available, the potential block areas can be taken as the slopes (computed from the DTM) which are steeper than a threshold value deduced from the analysis of slope histograms and observed rock instabilities (Rouiller & *al.*, 1998).
- At local scale (valley or catchment area), contrary to the mapping at regional scale, the identification of rockfall hazards can not result only from computer modelling. It has to be complemented by information about rockfall activity. This can be provided by aerial pictures, register of events, historical documents and quick field surveys.

For each homogeneous hazard area, based on the run-out areas computed with the cone model and on the indications of rockfall activities, four different run-out zones are distinguished and delineated:

(1) the proved run-out zone, where blocks are observed;
(2) the inferred run-out zone, computed with the cone model, but where no boulder is observed;
(3) the potential zone, which is probably not reachable by blocks even if it is difficult to prove it (e.g high reverse slope or near-vertical source above a flat relief);
(4) highly unlikely run-out zone, due to artefacts of the cone method such as the overestimation of the lateral extent of the zones that can be endangered by rockfalls.

This methodology of preliminary zoning at local scale is consistent with the hazard identification step of the Swiss federal guidelines for land-use planning in landslide-prone areas. It has the advantage to compile on a single map the systematic results computed with the cone method and indications about the rockfall activity .

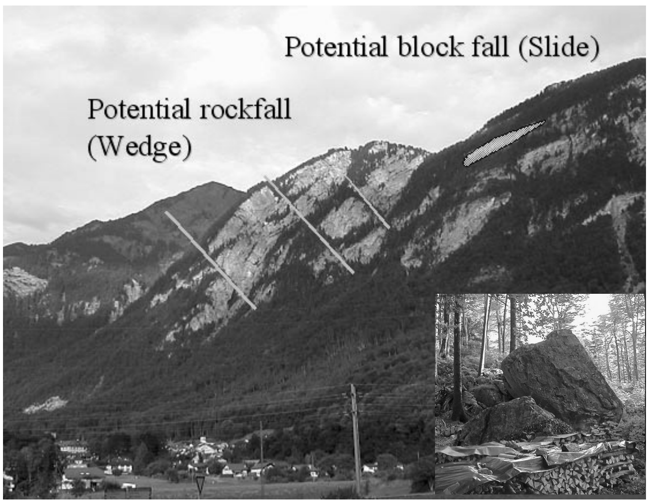

Figure 5: Picture down to the N-NE of the slopes above Lavey-Village and example of a 3 m diameter block found within the forest above Lavey, indicating activity.

Application to Lavey-Village, Vaud, Switzerland

As example, the methodology is applied to a homogeneous hazard zone above Lavey-Village (location shown in Figure 4) consisting of carbonates with potential wedges and slide on stratification failure mechanisms (Figure 5).

After the definition of the source pixels by merging cliff polygons from topographic vector maps and slopes steeper than 45°, the run-out area is computed with a cone aperture of 55° (Figure 6). These results are then compared with aerial photographs and rough field observations (deposits) to classify the run-out areas as proved, inferred, potential or highly unlikely (Figure 7).

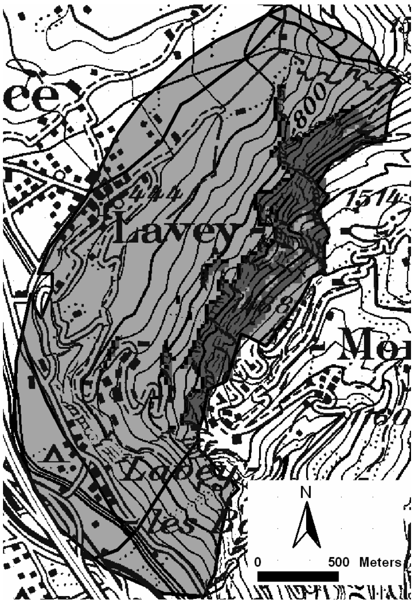

Figure 6: Example of run-out zone computed with the cone model for an angle $\varphi_p = 35°$. The dark grey corresponds to the source pixel area and the light grey to the run-out zone. The black pixels indicate the bottom of cliff pixels.

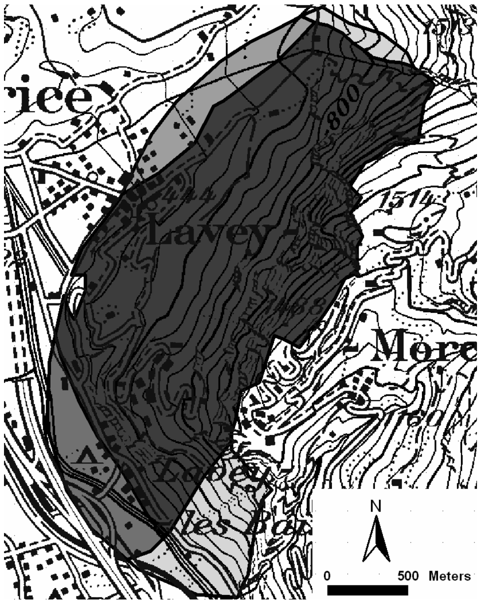

Figure 7: Example of preliminary zoning based on the computed run-out area of figure 6 (see text for the four classes). The darker grey corresponds to the proved run-out zone (1) and the lighter one to the highly unlikely zone (4).

The application of the alternative approach proposed by Evans and Hungr (1993) with a minimum shadow angle φ_p of 27.5° keyed to the bottom of the cliffs, yields a run-out area very similar, especially in the NW part, to the proved run-out zone delineated previously from the block deposits observed in the field (Figure 8). Note that in this computation the cones were limited to the direction [275°; 325°] in order to reduce lateral artefacts.

Figure 8 plots as well the velocities estimated from the maximum difference in elevation Δh between the several cones and the topography. The results are reasonable, ranging from 0 to 50 m/s. As a part of the kinetic energy is rotational, they nevertheless should be somewhat reduced.

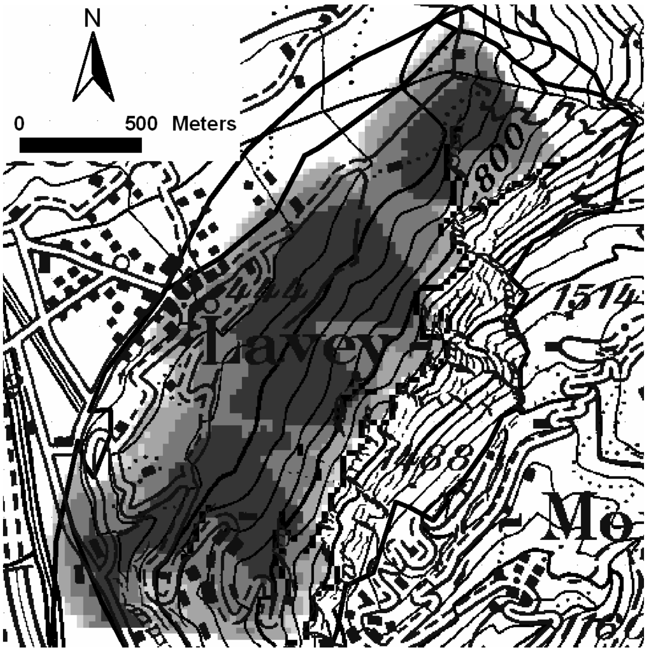

Figure 8: Estimation of run-out area and block velocities for an angle φ_p of 27.5° and cone apexes selected as the bottom of the cliffs (in black). The velocity classes are <12, <25, <38, <50 m/s (respectively from light to dark grey).

Conclusion

The rockfall Fahrböschung and shadow angle methods were proposed and used by several authors for the preliminary estimation of maximum rockfall reach. The so-called cone method is a simple 3D generalisation of these approaches. Based on DEM data, it allows to quickly compute the areas potentially endangered by rockfalls starting from a source. The method has been implemented in a freeware, called CONEFALL, which is available on the web.

The cone method is interesting at both regional and local scales for a preliminary hazard mapping. The objectives at regional scale are the early detection of conflicts between land-use and rockfall hazard as well as the identification, from a simple risk analysis, of the zones where detailed investigations are first required.

At local scale (valley or catchment area), the results from the cone model complemented with information on rockfall activity (e.g. deposits, register of events) allow to classify the run-out areas as proved, inferred, potential or highly unlikely. The proposed methodology is consistent with the hazard identification step of the Swiss federal guidelines for land-use planning in landslide-prone areas.

On the other hand, this hazard mapping methodology is too rough and consequently can not be used for the second step of the guidelines devoted to hazard assessment. Indeed, this part implies the determination of the magnitude and mean return period of events, which needs more detailed field investigations and numerical modelling.

As conclusion, the cone method is certainly a powerful tool for a preliminary, quick and low-cost, determination of areas endangered by rockfalls. However, as the predictions are largely conditioned by the equivalent friction angle φ_p (Figure 2), it is essential to carefully assess its value based on experience and field observations.

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