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REGIONAL ROCKFALL HAZARD ASSESSMENT IN THE BENASQUE VALLEY (CENTRAL PYRENEES) USING A 3D NUMERICAL APPROACH

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ABSTRACT

*Rockfall hazard assessment is a fundamental land planning tool in high mountain area. In this paper, a new rockfall hazard methodology is applied, based on the results of a 3D rockfall numerical model performed through an original simulation code. This is based on a lumped mass algorithm and allows to simulate rockfall motions in a spatially distributed way on a 3D topography described by a DTM. Model results can be combined in a GIS in order to produce physically based rockfall hazard maps according to a 3D matrix approach providing both a positional "hazard index" and a "hazard vector". The method has been tested at a regional scale in the Benasque basin, a 290 km^2 mountain area in the Huesca Province (Central Pyrenees, Spain). A DEM with cell size of 25*25 m has been used to describe topography. Information concerning lithology, geomorphology and vegetation of the area have been combined in a unique condition map to characterise the different slope materials and to identify outcropping areas and rockfall source areas. The model has been run with a stochastic approach and calibrated by geomorphological observations. Results have been combined in a 3D hazard rating matrix to obtain positional and vector hazard indexes. Different hazard maps has been produced in order to outline the exposed areas and to evaluate possible land planning solutions.*

1 INTRODUCTION

Rockfall hazard assessment is a fundamental land planning tool in high mountain areas, where human settlements progressively expand across rockfall prone areas, rising the vulnerability of the elements at risk, the worth of potential losses and the restoration costs. Nevertheless, the definition of rockfall hazard is not simple to achieve, since physically-based assessment methodologies are still missing. When coping with rockfalls, hazard assessment involves complex definitions for "occurrence probability" and "intensity". The local occurrence probability must derive from the combination of the triggering probability (related to the geomechanical failure susceptibility of rock masses) and the transit or impact probability at a given location (related to the motion of falling blocks). Rockfall intensity is a complex function of mass, kinetic energy and fly height of involved blocks that can be defined in many different ways depending on the adopted physical description and "destructiveness" criterion. In this paper, a new rockfall hazard assessment methodology has been applied at the regional scale to the study area of the Benasque Basin (Spain), in order to give a preliminary evaluation of the rockfall hazard and risk in the area.

2 3D NUMERICAL MODELLING OF ROCKFALLS

Rockfall dynamics is a complex function of the initial position and the geometry and mechanical properties of the block and the slope. Nevertheless, the relevant parameters are hardly ascertained both in space and time, even for an observed event. Usually, the geometrical and geomechanical properties of the blocks and the slope, and the exact location of the source areas are unknown and characterized by extreme variability. In addition, the energy lost at each impact or during rolling depends on a variety of factors. These parameters are difficult to determine at any spatial scale. Thus, "contact functions" relating the kinematics of the block or its dynamics before and after each impact, are introduced to model the energy loss. These functions are expressed as restitution and friction coefficients and regarded as material constants even if they include many different effects. The 3D nature of actual slope geometry strongly affects the trajectories and the partition of kinetic energy into translational and rotational components. Moreover, since rockfall trajectories are usually computed along few, user-defined 2D profiles, the interpretation of results and its extension to neighbouring areas require extensive engineering judgement (Cancelli & Crosta, 1993).

Keeping in mind the aforementioned problems, an original 3D rockfall simulation program (STONE) has been developed (Agliardi & Crosta 2002; Guzzetti et al., 2002). The software was conceived to perform a large number of simulations of 3D rockfall paths using a simple kinematic modelling approach rather than a sophisticated dynamic one.

The program is based on a lumped mass (kinematic) algorithm. Topography is provided as a raster Digital Elevation Model and input data are in a spatially distributed form. Pseudo-random stochastic modelling is allowed and recently a new scaling relationship for evaluation of restitution coefficients has been implemented within the code.

Both 2D (raster) and 3D (vector) outputs are provided. Raster maps portray at each cell: the cumulative count of rockfall transits, the maximum computed velocity and the largest flying height. Vector outputs provide instantaneous velocity and fly height at each point sampled along the computed fall paths.

3 ROCKFALL MODELLING IN THE BENASQUE VALLEY

The Benasque Valley is located in the Huesca Province (Central Pyrenees, Aragona, Spain; see Figure 1) and takes an area of about 290 km^2. The area is an important ski resort and it includes the National Park of the Posets-Maladeta and the highest peak in the Pyrenees (Mt Aneto, 3404 m a.s.l.). The two main urban centres within the study area are Benasque and Eriste, both located in the lower part of the valley.

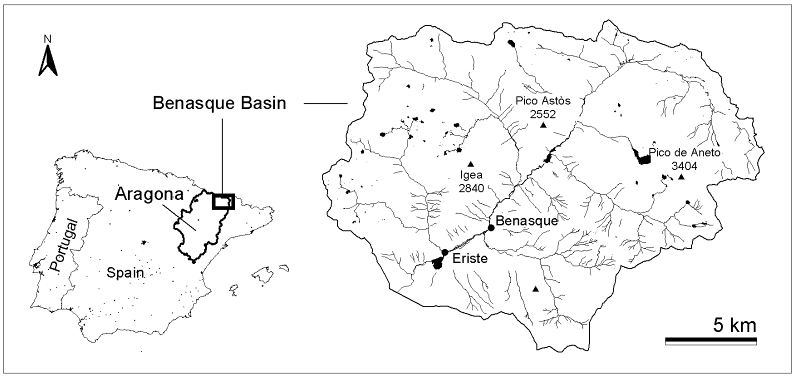


Figure 1. Location map of the Benasque study area.

Palaeozoic rocks crop out in the area. Slate, limestone, granite and some sandstone outcrop in the northern part of the area, covered by widespread glacial, fluvial and colluvial Quaternary deposits. Slates prevail in the SE sector of the study area. These units belong to the Pyrenean Axial Zone and have been affected by the Hercinian and Alpine orogeneses. Rocks are tectonically piled up southwards through Alpine age thrusts and are strongly folded, faulted and metamorphosed. The predominant Palaeozoic structure, trending WNW–ESE, is interrupted or cut by three granodiorite batholites intruded during the late Hercinian orogeny and by a devonian subvolcanic complex, namely: the Maladeta Granite Massif (to the East), the Posets-Millares Granite Massif (to the West), the Lys Granite Massif (to the North), and the Cerler Volcanic Complex (to the South, rhyodacite intrusion).

Morphology is the result of glacial and recent periglacial processes, controlled by lithological and structural features. The Last Glacial Maximum took place 40.000 years ago (Bordonau, 1992; Chueca et al., 1998). Glacial and periglacial morphologies are more frequent and relevant in the northern sector, where granites outcrop and where the highest altitudes are reached. The Benasque Valley is one of the best examples of glaciated valley in the Pyrenees.

Nowadays, few examples of small active glaciers exist. Among the slope morphologies, many landslides, talus deposits, debris cones, rockfall blocks and debris flows have been mapped. The fluvial morphology consists of fluvial incision and of active and inactive alluvial fans. Tectonic fractures, faults and unloading joints subdivide the different lithologies inducing frequent rockfalls from major rocky cliffs.

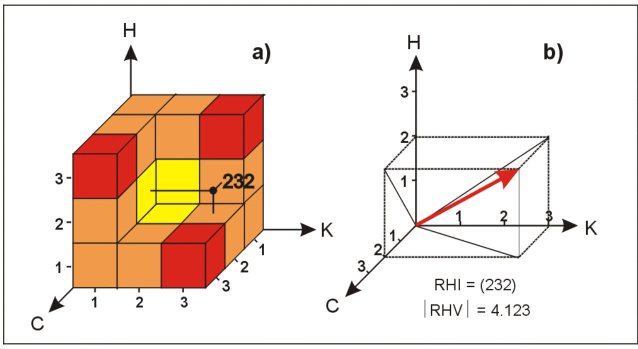
The proposed numerical approach to rockfall modelling requires a series of input data. For the Benasque area we have prepared a set of maps including: geology, geomorphology, land use and vegetation cover. A 25*25 m DEM has been prepared as well as two different rockfall source maps. Maps have been recoded to create a unique condition map with a total of 22 classes. Then, values of restitution and of friction coefficients have been attributed to each class.

Rockfall sources have been outlined according to two different approaches: a first rockfall source map has been obtained starting from simple morphometric assumptions (slope > 43° in outcropping rock areas) and a second map from direct aerial photo interpretation.

Rockfall modelling has been performed through STONE using a stochastic approach (Figure 3a, b, c). The model was calibrated using the available geomorphological information (location of mapped largest rockfall blocks and talus extent). As a result, 76% of talus areas are affected by computed trajectories and 70% of the largest blocks were along the trajectories.

4 ROCKFALL HAZARD AND RISK ASSESSMENT

A new rockfall hazard assessment methodology (Crosta & Agliardi, submitted) has been applied, based on the results of numerical modelling. As mentioned, the code provides raster maps portraying the maximum frequency of transit, velocity and height of blocks at each model cell (Figure 3a, b, and c). In this example we used the raster outputs because of the unsuitability of vector data for a regional scale study due to hardware and software limitations. The methodology is based on a 3D matrix with rockfall count (C), translational kinetic energy (K) and fly height (H) along the axes, providing a positional Rockfall Hazard Index (RHI), which simply includes a reference to each class value into a three digit number (Figure 2a), and a Rockfall Hazard Vector (RHV) magnitude value for each DEM cell (Figure 2b). The Rockfall hazard Vector (RHV) doesn't allow to separate the different contribution of each controlling parameters to rockfall hazard, but it points out the level of hazard allowing a simpler and more objective ranking.



c)

class	c (normalised)	k	h
-	-	(kJ)	(m)
1	< 0.2	< 700	< 4
2	0.2 – 1	700 – 2500	4 - 10
3	> 1	> 2500	> 10

Figure 2. Basic concepts underlying the proposed hazard assessment methodology: a) 3D hazard matrix and Rockfall Hazard Index (RHI); b) definition of the Rockfall Hazard Vector (RHV); c) adopted parameter reclassification scheme.

The input parameters (i.e. the rockfall count, the maximum kinetic energy and the highest fly height, computed at each cell) are reclassified according to the scheme proposed in Figure 2c. The reclassification is based on the evaluation of different levels of destructivity with respect to structures (buildings) and passive countermeasures (retaining fills, rockfall barriers), and allow to combine the parameters in a RHI index and to compute the magnitude of the RHV vector, required to rank hazard.

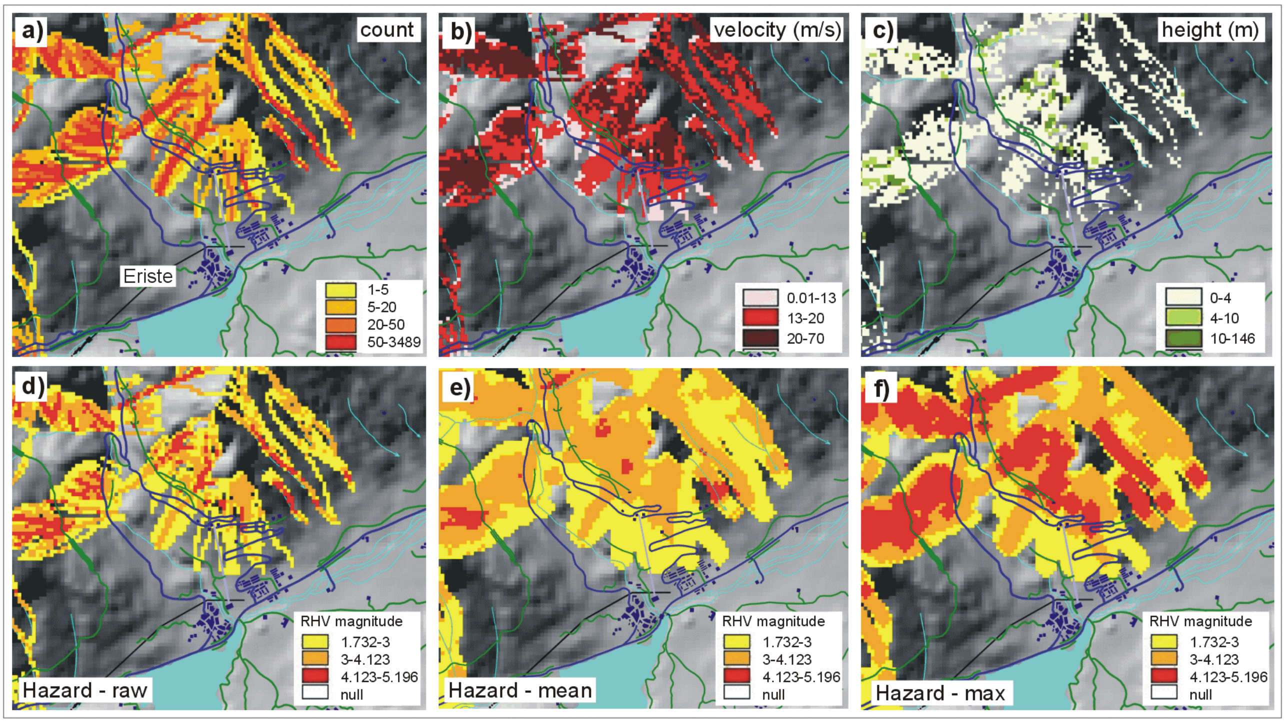


Figure 3. Close-up of the rockfall model in the Eriste area: a) rockfall count raster map; b) maximum computed velocity raster map; c) maximum computed height raster map. Hazard maps obtained through the proposed methodology: d) raw map, directly computed; b) map smoothed by the mean value (50 m neighbourhood); c) map smoothed by the maximum value (50 m neighbourhood).

Different hazard maps have been obtained using raster maps computed by STONE (Figure 3a, b and c). Hazard computation according to the proposed methodology allowed to obtain a “raw” hazard map (figure 3d). In order to achieve a more effective hazard zonation, the raw hazard map has been “smoothed” by the mean and the maximum RHV magnitude, respectively computed in a 50 m neighbourhood.

A preliminary assessment of rockfall risk is given in Table 1, where percentages of different elements at risk involved in areas characterised by different hazard level (i.e. RHV value range) are reported. Such a definition of risk include hazard and the evaluation of categories of elements at risk characterised by different relative worth. Nevertheless, the analysis doesn’t incorporate vulnerability and true economic worth, and assumes a constant value of exposure. Thus, we retain that this could be considered as a first step towards a more sound evaluation of rockfall risk.

HAZARD		**ELEMENT AT RISK**					
RAW HAZARD MODEL							
		Tracks	**Ski-lifts**	**Penstock**	**Powerline**	**Road**	**Urban area**
RHV range	**% total area**	**% involved**	**% involved**	**% involved**	**% involved**	**% involved**	**% involved**
1.73 – 3	14.5	11.2	5.1	59.5	-	7.1	3.8
3 – 4.12	6.9	3.3	-	-	-	3.3	0.3
4.12 – 5.20	4.3	1.0	-	-	-	1.0	0.3
null	74.3	84.5	94.9	40.5	100	88.6	95.6
SMOOTHED HAZARD MODEL: Mean value (50 m neighbourhood)							
		Tracks	**Ski-lifts**	**Penstock**	**Powerline**	**Road**	**Urban area**
RHV range	**% total area**	**% involved**	**% involved**	**% involved**	**% involved**	**% involved**	**% involved**
1.73 – 3	17.6	19.8	9.5	72.5	-	13.6	7.7
3 – 4.12	17.8	7.9	-	-	-	9.0	1.4
4.12 – 5.20	2.0	0.3	-	-	-	0.6	0.2
null	62.6	72.0	90.5	27.5	100.0	76.4	90.7

Table 1. Preliminary risk assessment for the Benasque Valley.

5 CONCLUDING REMARKS

A new rockfall hazard assessment methodology (Crosta & Agliardi, submitted) has been applied at the regional scale in order to give a preliminary zonation of the areas more prone to rockfall hazard and risk in an important mountain resort of the Spanish Pyrenees. The methodology is physically based, objective and easy to apply at the regional scale with a low budget geomorphological data collection. The application of the methodology to the Benasque Valley allowed to outline that the facilities are prone to low rockfall risk and, thus, are suitable for further developments. Nevertheless, some sectors of urbanised areas and transportation corridors (roads and mountain tracks) are subjected to medium to high rockfall risk. The performed analysis proved to be useful to outline these sectors, allowing to optimise budgets for maintenance and remediation.

REFERENCES

Agliardi, F. & Crosta, G.B. 3D numerical modelling of rockfalls in the Lecco urban area (Lombardia Region, Italy), *Proceedings EUROCK2002, I.S.R.M. International Symposium on Rock Engineering for Mountainous Regions*, Madeira, Portugal, 2002.

Bordonau, J. Els complexos glacio-lacustres relacionats amb el darrer cicle glacial als Pirineusm, *Geoforma*, 1992.

Chueca, J, Peña, J.L., Lampre, F., García-Ruiz, J.M. & Martí, C. Los glaciares del Pirineo aragonés: estudio de su evolución y extensión actual. Departamento de Geografía y Ordenación del Territorio de la Universidad de Zaragoza, 1998.

Cancelli, A. & Crosta, G.B. Hazard and risk assessment in rockfall prone areas, *Risk Reliability in Ground Engineering*, ed. Skipp, B.O., Inst. Civ. Eng., Thomas Telford, London, 1993, pp. 177-190.

Crosta, G.B. & Agliardi, F. A methodology for physically based rockfall hazard assessment. *Natural Hazards and Earth System Sciences*, submitted.

Guzzetti, F., Detti, R., Crosta, G.B. & Agliardi, F. STONE: a computer program for the three dimensional simulation of rock-falls. *Computers and Geosciences*, 2002, 28, 1079-1093.