USING GEOMATICS AND AIRBORNE LASER SCANNING FOR ROCKFALL RISK ZONING: A CASE STUDY IN THE FRENCH ALPS

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KEY WORDS: Rockfall, Risk Zoning, Airborne Laser Scanning, Protection Forest

ABSTRACT:

In mountainous areas, rockfalls represent a major threat to human safety, public infrastructures and economic assets. Accurate mapping and qualification of risk areas are required so that public authorities can make secure and efficient decisions regarding town planning schemes. In France, Risk Prevention Plans (PPR) are standard documents that determine risk areas and building authorisations for ten-year periods. During the PPR revision of the town of Veyrier-du-Lac (France), we implemented a new methodology based on geomatics for rockfall risk assessment. Analysis of airborne laser scanning data, field data and 3D rockfall simulations was performed with geographic information system (GIS) to accurately map hazard areas and their associated intensity and frequency. Decision makers could then interactively discuss the implications of different hazard thresholds before the final risk maps were edited. The coordination of information in a GIS improved the interactions between experts and decision makers. The use of high resolution data and algorithms allowed a fine zoning of risk maps with quantification of forest protection effect in a complex environment.

1 CONTEXT

1.1 Introduction

In alpine environments, natural hazards such as rockfalls are common but unpredictable events. To protect human lives and infrastructures without hampering town development and economic activities, public authorities must adequately map risk zones and take them into account in town development schemes. Thanks to the increasing processing power of computers and new methodological developments, trajectory simulation models are now increasingly used with the aim of making rockfall hazard maps (Jaboyedoff et al., 2005). However, few rockfall trajectory simulation codes accurately include the effects of both the topography and the forests stands in the propagation of falling rocks (Dorren, 2003; Dorren et al., 2006). Lan et al. (2010) showed the advantages of using a Digital Terrain Model (DTM) obtained by Airborne Laser Scanning (ALS) for assessing hazards over long railway sections in Canada. ALS is an active remote sensing technique used to produce high resolution DTM but also for forest parameters estimation (Hyyppä et al., 2008). However these methods often remain research tools and are seldom implemented for operational or commercial purposes.

1.2 French context: the Risk Prevention Plan

Since 1995 in France, each town subjected to natural hazards must update its Risk Prevention Plan (PPR) every ten year (Garry et al., 1997). A PPR is a legal document which maps and defines the risk zones. It aims at taking into account natural hazards, such as rockfalls, avalanches or floods in town planning schemes. A PPR includes risk maps with detailed explanations about their characteristics. Four risk zones are defined according to hazard levels which depend on hazard frequency and intensity (Table 1).

Color code	Hazard level	Construction possibilities
Red	High	None
Blue	Medium	Under architectural constraints
White	Low or none	New constructions allowed
Green	Potential protection forest	

Table 1: Risk zones in a Risk Prevention Plan

Regarding rockfall risk zoning, common practices rely on a limited number of 2D numerical simulation results manually extrapolated to whole hillsides. In areas such as the French Alps, with highly variable topographic and soil conditions, such approaches may overlook local effects which have decisive consequences on rock propagation. Moreover the protective function of forests is frequently underestimated or even ignored.

1.3 Study area

The object of this study is the PPR revision of the town of Veyrier-du-Lac (France, Haute-Savoie, 45°52'54"N, 06°11'57"E). Town area is about 8 km^2. Residential areas are located at the footslope between the Annecy lake located at the South-West and 4 km long overhanging cliffs oriented NW–SE (Figure 1). Altitude ranges from 440 to 1300 m, with 150 to 200 m high limestone cliffs. Forest covers the hillside and about 80% of the area. Because of this complex environment and of the neighbouring city of Annecy, local authorities of Veyrier-du-Lac deal with a high residential real estate demand and a limited amount of available terrain surface. Besides, rockfalls occur rather frequently in the area. Since 1950, about 23 rockfall events have been recorded, hopefully without any human casualties. No rockfall simulations were performed for the establishment of the previous PPR in 1994. In 2007, the town mayor asked the state authorities to revise the

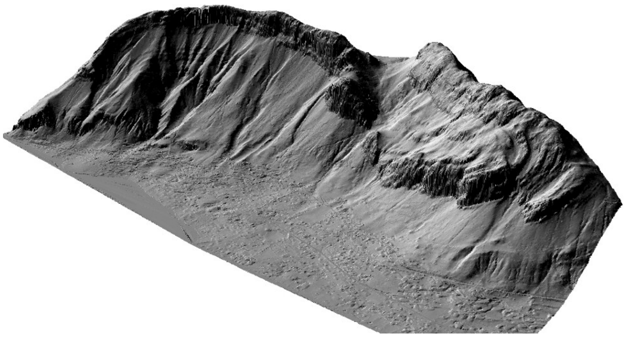


Figure 1: Shaded overview of the digital terrain model of the study area

PPR. An emphasis was put on the need for a trajectory study, so that the maximal run out envelop of rockfalls would be defined and risk zones accurately integrated in the town planning scheme. In order to meet this objective and test the limits of new remote sensing and simulations tools, we developed a methodology based on the cross analysis of airborne laser scanning data, field data and 3D rockfall simulations using Geographic Information System (GIS). The workflow is detailed in Figure 2.
The objectives of this article are :
- to present the methodology implemented to revise the PPR;
- to evaluate the technical advantages of using high resolution data and 3D simulation tools for risk zoning;
- to discuss the added value of geomatics as a central tool in a decision making process involving public authorities and technical experts.

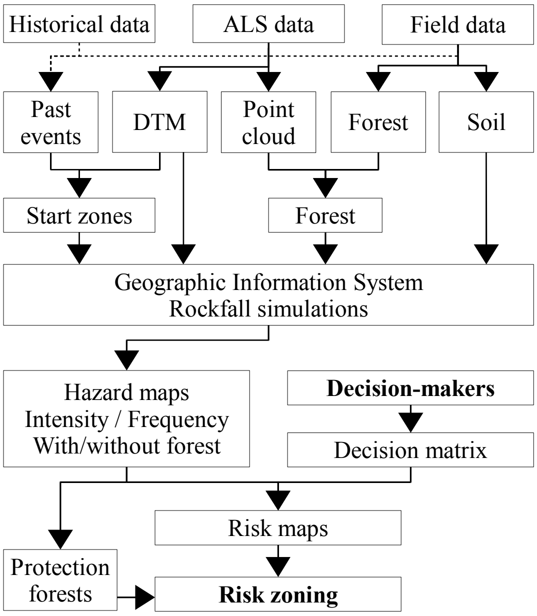


Figure 2: Workflow of the risk zoning methodology

2 MATERIAL

2.1 Historical and official data

Historical data are the main source of information to assess the intensity and frequency of rockfalls. The Service de Restauration des Terrains de Montagne (RTM) of the French Forest Commission has recorded all major events since 1882. From 1950 to 2008, 23 events were recorded in Veyrier-du-Lac. 52% of the rocks reached a road or a building. Historical data and observation of rocks on the ground give information on the individual volume and propagation distance of rocks. During a preliminary meeting, local authorities decided that the reference hazard would be the event with occurrence probability of 10^{-2} year^{-1} (centennial event).
The ground occupation map includes all present human facilities: industrial, commercial, residential and agricultural areas, public buildings and transport and communication infrastructures. This information is extracted from the BD TOPO®of the French National Geographic Institute (IGN) or from existing town planning schemes maps.

2.2 Airborne laser scanning data

The laser data was acquired during late summer 2008. Acquisition parameters are summarized in Table 2. The point cloud was classified into ground and non-ground echoes using the TerraScan software. Final echo density was 10 m^{-2}. A DTM of metric resolution was computed by linear interpolation of ground echoes over a regular grid.

Item	Value
Scanner model	RIEGL LMS-Q560
Wavelength	1550 nm
Pulse repetition rate	200 kHz
Scan frequency	111.1 Hz
Scan angle	± 30°
Flight height	550 m
Laser footprint	0.29 m
Theoretical point spacing	0.47 m

Table 2: Laser scanner acquisition parameters

2.3 Field data

Whatever the number of historical data or the precision of remote sensing data, it is necessary to undertake field surveys to establish the ground truth required to calibrate the forest parameters estimation models, measure local soil characteristics and get additional information about the size and frequency of rockfalls. 104 circular plots of 10 m diameter were inventoried between October and December 2008. Plots were distributed every 100 m along the 500, 700, 900 and 1100 m contour lines of the hillside. In each plot the following features were inventoried:
- forest: species and diameter at breast height (DBH) of trees with a DBH larger than 7.5 cm;
- landform: macro topography type, micro topography roughness, mean obstacle height, soil stiffness;
- rockfall activity: number, shape and size of recently deposited rocks, and number and height of rock impacts on trees.

Forest stand attributes were then computed for each plot: mean diameter at breast height ($\overline{dbh}$), its standard deviation (σ_{dbh}), basal area (G) and stand density (N). Moreover, a dendrochronological study was undertaken to evaluate rockfall activity below one particular cliff. On eight plots located at the cliff foot and along the rockfall corridor, 20 trees were nicked to estimate the number and age of impacts (for a description of dendrochronology applied to rockfall assessment, see Stoffel et al., 2005).

3 METHODS

3.1 The Rockyfor3D model

Rockyfor3D is a simulation model that calculates trajectories of single, individually falling rocks, in three dimensions (Dorren et al., 2005). The model combines physically-based algorithms with stochastic approaches, which makes Rockyfor3D a so-called "probabilistic process-based rockfall trajectory model". Rockyfor3D can be used for regional, local and slope scale rockfall simulations. It simulates the rockfall trajectory by calculating sequences of classical parabolic free fall through the air and rebounds on the slope surface, as well as impacts against trees if required. Rolling is represented by a sequence of short-distance rebounds and sliding of the rocks is not modelled. The required input data consists of a set of ASCII rasters (ESRI format), which define slope surface, forest and block characteristics and topography. The main components of the model are the parabolic free fall, the rebound on the slope surface, the impact against a tree and the calculation of the fall direction (Bourrier et al., 2009). Each time a simulated block surpasses or rebounds in a given raster cell, statistics of the block trajectory in that cell are recorded.

3.2 Forest parameters estimation

The method proposed by Næsset (2002) was implemented to estimate forest stand parameters ($\overline{dbh}$, σ_{dbh}, G and N) over the study area. Laser metrics (height distribution quantiles of laser points) are computed for the point clouds extracted over each georeferenced field plot. Multiple regression models with forest parameters as dependant variables and laser metrics as predictors are then fitted by ordinary least squares with stepwise variable selection. Estimates of each forest stand parameter at a given scale are then predicted on the entire area using the established regression models and whole point cloud.

3.3 Data preprocessing using GIS

Data collected during the field surveys were integrated and preprocessed in GIS software ArcGIS 9.2. Plot centers were georeferenced and imported in vector format with their attributes table. Concerning soil characteristics (roughness, stiffness, mean obstacle height) and broadleaved/coniferous proportion, estimated values on a regular grid were computed from the irregularly localised sample points using nearest neighbour interpolation. The topography and the slope surface rasters were calculated from the metric resolution DTM.

Regarding rockfall characteristics input files, block size and density were defined by analysis of the historical data and field observations. Due to the high number of cliffs, the localisation of potential start zones was determined by DTM modelling, instead of comprehensive field observation or photo interpretation. Slope was computed from the DTM and a threshold was applied to the resulting raster: all cells with values higher than the threshold were qualified as potential release zones. The threshold slope α has been defined in the European project Provialp (Cemagref and Arpa, 2006) and depends on the DTM resolution RES (1).

$$\alpha = 55 \times RES^{-0.075} \tag{1}$$

3.4 Rockfall simulation

All input rasters were resampled at the same resolution and extent before they were supplied to the Rockyfor3D simulation tool. A trade-off between computation time, spatial level of details (raster resolution) and statistical robustness (number of simulations) had to be found. One set of simulations was launched with integration of forest effect: Rockyfor3D uses stand parameters to simulate in each cell the number, position and diameter of trees. An other set was launched without taking into account the forest effect. In each case, the following output rasters were created:

- mean and the 95th percentile of the kinetic energy (kJ) of passing blocks,
- mean and the 95th percentile of the normal path height (m) of passing blocks,
- event frequency,
- volume of the biggest block deposited in cell (m^3).

The maximum run out envelope of rockfalls was compared to historical data to ensure that simulation results were consistent with field observations.

3.5 Participative analysis of results

Localisation, intensity and frequency are the three main characteristics of hazards. In order to map hazard zones in a synthetical manner, hazard levels were defined by cross analysis of frequency and intensity classes. In this study we adopted the kinetic energy classes used by the Swiss Confederation for hazards maps (OFAT, 1997). Four frequency classes were also defined. Three hazard levels are defined by combining the kinetic energy and frequency classes (Table 3). These hazard levels are used to define the PPR risk zones (Table 1).

	Kinetic energy E		
Frequency F	$E \leq 30$	$30 < E \leq 300$	$300 < E$
$F \geq 10^{-2}$	medium	high	high
$10^{-2} > F \geq 10^{-4}$	medium	medium	high
$10^{-4} > F \geq 10^{-6}$	low	medium	medium
$10^{-6} > F$	low	low	medium

Table 3: Hazard levels determined by combination of rockfall kinetic energy and frequency classes

4 RESULTS

4.1 Simulation inputs

The 1 m resolution DTM was used to determine start zones based on the slope criterion. According to Equation (1), all cells with a slope value higher than 55° where considered as potential start zones. The selected pixels were distributed all along the cliffs of Veyrier-du-Lac and their position was consistent with field observations and historical data. The past events analysis also showed that the block volume corresponding to the centennial event (reference hazard) depended on the localisation. Therefore, the study area was divided into nine zones before simulating: seven zones with a block volume of 1 m^3, one zone with 2 m^3 blocks and one zone with 5 m^3 blocks. Before each individual rockfall simulation the block volume is sampled from a uniform distribution centered on the reference volume of the start area with ± 30% variation. In order to reduce computation time for the total area of 8 km^2, the DTM was resampled to 5 m resolution. Experience showed that a 1 m resolution DTM does not necessary improve the quality (Dorren and Heuvelink, 2004). From each potential start point, 500 rockfalls trajectories were simulated on bare soil, and 500 more with integration of forest effect.

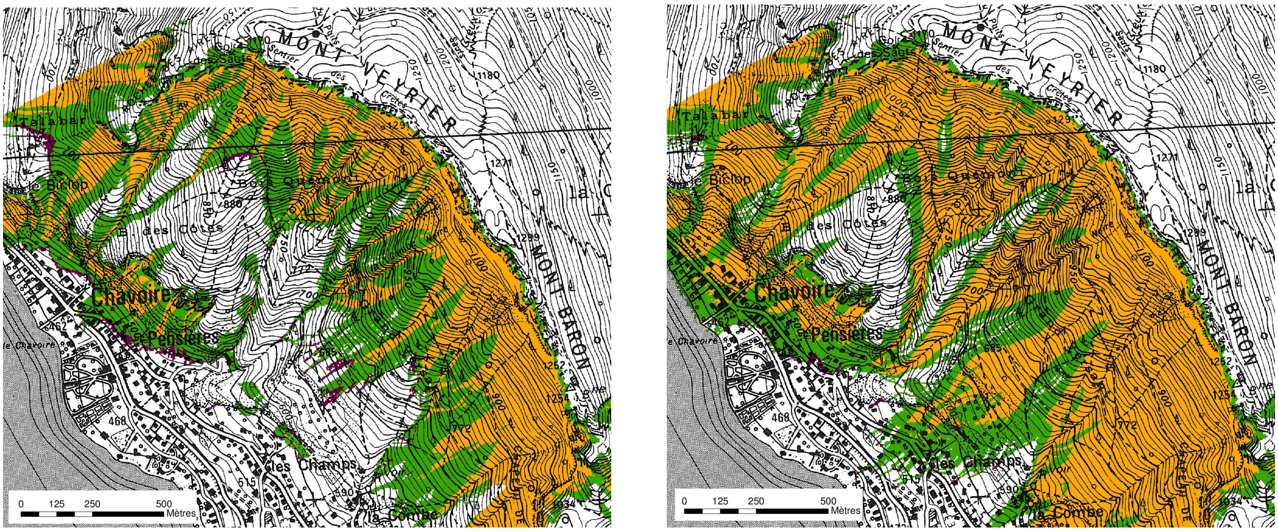
4.2 Simulation maps

Comparison of the run out envelopes obtained with and without forest integration shows that the current vegetation cover reduces rock propagation in sectors where the block volume of the centennial event was 1 m^3. However, in such areas, the effect is noticeable only when rocks fall through forest areas longer than 250 m.

When comparing maps of event frequency with and without forest integration, it turns out that trees affect the lateral deviation of blocks. In thalwegs vegetation increases the concentration of block trajectories toward the steepest slope direction, whereas blocks are more scattered in homogeneous hillsides.

Regarding maps of mean kinetic energy of blocks, it is noteworthy that the mean energy is significantly reduced in sectors where the centennial reference volume is 1 m^3. The value of 95th percentile of the kinetic energy (extreme events) is reduced in the forest case only in deposit zones. Besides, higher energies are observed in a small number of pixels when forest is taken into account. This phenomenon is linked to the forest dispersal effect mentioned above.

There was no significant difference regarding passage height between the two sets of simulations.



(a) With forest integration

(b) Without forest integration

Figure 3: Hazard levels map obtained by combination of rockfall kinetic energy and frequency classes. Only the northern part of the study area is represented. Colors are defined in Table 3.

A GIS cross analysis is performed with kinetic energy and frequency maps to obtain the hazard levels maps with and without forest integration (Figure 3). These maps are presented to decision makers, who can discuss the hazards levels before the final risk zones are edited (Figure 4).

5 DISCUSSION

5.1 Advantages of 3D simulation and airborne laser scanning data

With respect to current 2D methods implemented for rockfall hazard zoning, the simultaneous use of 3D simulation tools and airborne laser scanning data brings major advantages. Topographic effects on rock propagation are precisely modelled thanks to the simulation of individual block trajectories on a high resolution DTM. Moreover the combination of field observations and laser data allows a better description of the forest characteristics and start points localisation with reduced field campaign. Thanks to the high number of simulations, the spatial distribution of the events frequency and intensity is available at 5 m resolution.

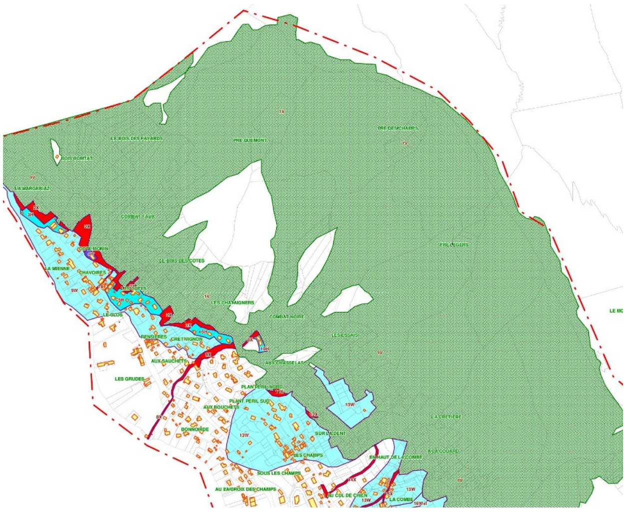


Figure 4: Risk zones map after decision-makers agreement. Colors are defined in Table 1.

However, the need for precise field observations remains crucial in this methodology. Historical data are required to estimate the block volume of the reference risk and to validate the start zones and run-out envelopes of the simulations. Calibration of regression models used to estimate forest parameters from laser data also depends on careful sampling of forested areas. Moreover, field observations are currently the only way to map local soil characteristics (roughness, stiffness, and obstacle height). Interpolation methods used to estimate these variables on the whole area may be improved by taking into account the macro topography (slope, landform) characterised with high resolution DTM. Besides, frequency results are based on the implicit assumption that rockfall occurrence probability is equal for every start point. Indeed, when whole hillsides are studied, it seems rather difficult to reach a comprehensive knowledge of the geological state of potential start zones and to be able to estimate a rockfall probability function depending on both the spatial localisation of points and block size.

5.2 Geomatics in the decision making process

Maps of risk levels superimposed on ground occupation are presented to the public authorities. Decision makers can then discuss which risk level is acceptable or not in different areas and possibly modify the thresholds between intensity or frequency classes. Besides, the areas where the forest protection function is significant (green zones) can be determined by comparison of the risk zones obtained with or without integration of the effect of forest cover. It reinforces public awareness that an adequate forest management is required to strengthen and make durable the forest protection effect.

The integration of all the information in a GIS allows an interactive process where the effects of threshold modifications can be instantly visualised on the cartography of the PPR project (Figure 4). This tool facilitates the participative decision process involving experts focused on technical criteria and public authorities interested in the resulting policy decisions. Moreover it acts as a central tool for the coordination of information and increases the possibilities of files sharing with respect to future update studies or information development.

6 CONCLUSIONS AND FUTURE WORK

Thanks to the geomatics-based methodology implemented in this study, decision makers are involved in the technical part of the zoning process. This participative approach, combined with the added value of high resolution data and tools, proved to be a successful experience in a highly demanding context.
As airborne laser scanning data remains a costly investment, future work will focus on taking a maximum advantage of this technology: design of an optimised operational protocol combining field and laser data, and extraction of additional landform information.

ACKNOWLEDGEMENTS

This work was funded by the Direction Départementale des Territoires (Haute-Savoie, France).
We thank Eric Mermin, Pascal Tardif, Jérôme Lopez, Christophe Bigot and Oliver Jancke for field data collection. Thanks also to Sintegra Photo (Meylan) for the acquisition and preprocessing of laser scanning data. Jean-Matthieu Monnet held a doctoral fellowship from Région Rhône-Alpes.

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