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Rock Slopes Failure Susceptibility Analysis: From Remote Sensing Measurements to Geographic Information System Raster Modules

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Abstract: Problem statement: Two important step can be recognised in the rockfall analysis: the potential failure detection and the run out simulation. Analyzing the stability of rock slopes, most important kinematisms are planar or wedge slidings and topplings. The aim of this study was to coupling a deterministic approach for landslide initiation (potential rockfall source areas) with a run-out analysis by developing new GRASS GIS raster modules. A case study in the Ossola Valley, at the border between Italy and Swiss, was discussed. **Approach:** New GIS raster modules for rockfall analysis were developed. Slope stability modules were based on rock mass classification indexes and on limit equilibrium model, while the prediction of rockfall travel distance was based on the shadow angle approach. **Results:** The study highlighted the importance of GIS tools for analysis of landslide susceptibility. The spatial forecasts provided by the new GIS modules were validated and supplemented by traditional analysis. **Conclusion:** This study proved that there is a good correspondence between the prediction of high attitude to instability calculated by the modules and the location of past events. The new modules have provided an opportunity to assess, in an objective and repeatable way, the susceptibility to failure and also quantitative information about area of invasion for rock falling.

Key words: Landslide susceptibility, rockfall, rock mass characterization, natural hazard, open source.

INTRODUCTION

Rockfalls are a major hazard for highways in mountainous areas, especially in the Alps where life line and population are widespread (Huat and Jamaludin, 2005). They don't pose the same level of economic risk as large scale landslides but, often, in association with debris flow, rock falls cause a significant number of accidents, damages and, unfortunately, fatalities.

The study area is located in the North-Western Alps, on the border between Italy and Swiss at about 800 m of elevation in a secondary valley connecting Piemonte and Valais. The unstable cliff, entirely made of gneiss and up to 250 m high, is located above the Frontier Guard station and the Sempione highway. Also a small hydro-eletric power plan and a dimensional stone quarry are close to the hazardous area. The area is affected not only by rockfalls but also by debris-flow and ice-falling in the spring time (Fig. 1).

The cliff can be referred to the Lower Pennine Nappe Complex, here represented by the orthogneissic nappe of Antigorio. The rock type is a granitic to granodioritic orthogneiss with medium grain size, generally marked by planar foliation and augen texture: it represents one of the most important and extensively exploited dimension stone in Italy (Cavallo *et al*., 2004).

The definition of hazard as the probability of occurrence of a phenomenon of certain intensity in a given area and within a given period of time (Varnes, 1984), is the methodological basis for the development of methods for assessment and hazard zonation (Longo and Oreste, 2010). Dealing with rockfalls, the temporal prediction of occurrence is especially complex. For these reason, researches focus their attention on spatial zonation in order to quantify relative hazard (Mandrone, 1995; Jamaludin *et al*., 2006; Mandrone *et al*., 2007) and most of them are free from time considerations. Also in this case the time factor is not considered.

MATERIALS AND METHODS

The approach used in this study consist in two basic steps: Identification of source areas of failure

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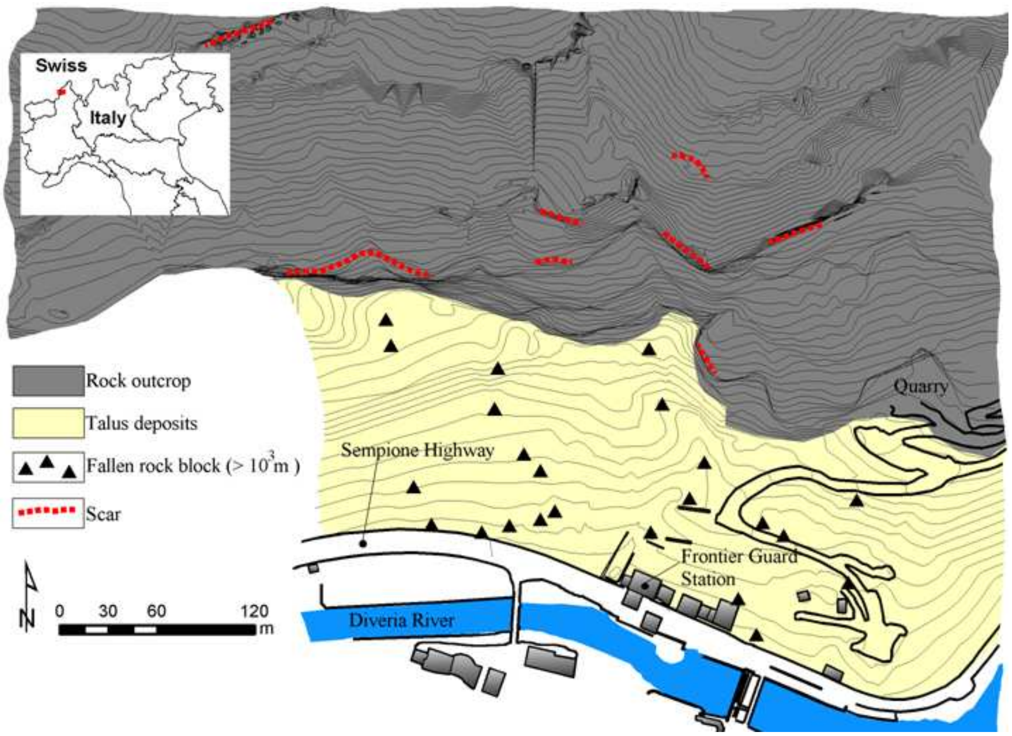

Fig. 1: Geographic location and sketch map of the study area

Table 1: List of the proposed modules and their main features

I.D. code	Analysis	Approach	Result
r.SMR	Planar sliding,Toppling	Slope Mass Rating (SMR) developed by (Romana, 1993)	Maps of the SMR index for toppling and planar failures
r.SSPC	Planar sliding Toppling	Slope Stability Probability Classification (SSPC) developed by (Hack *et al*., 2002)	Susceptibility raster maps for toppling and planar failures
r.wedgeSRM r.wedgeSSPC	Wedge sliding	Respectively the same as r.SMR and r.SSPC but applied to a wedge failure on two intersecting discontinuities	SMR or SSPC susceptibility raster map calculated for the line of intersection between two discontinuities
r.fsplanar	Planar sliding	Limit equilibrium analysis for a planar failure with no tension crack (Hoek and Bray, 1981)	Susceptibility raster map based on the spatial distribution of safety factors
r.droka	Flow (runout)	Shadow angle model (Evans and Hungr, 1993)	Kinetic energy and speed raster maps

analyzing the stability conditions for rock masses (the occurrence and the definition of the degree of instability of each kinematism is defined both by empirical criteria based on rock mass classifications than in terms of safety factor, using limit equilibrium methods) and analysis of the maximum propagation of rockfall as soon as quantification of the intensity of the process in terms of velocity and kinetic energy using, in three-dimension, the zenithal method (Evans and Hungr, 1993).

The calculation procedures were implemented as raster modules of a open-source GIS (GRASS), a very useful software also for many purpose (Jabbar and Chen, 2005; Filipello *et al.*, 2006; Hasmadi and Taylor, 2008). All developed modules are based on grid calculations on a pixel basis. Modules are, respectively, called *r.SMR*, *r.SSPC*, *r.wedge*, *r.fsplanar* and *r.droka* (Table 1).

Rock mass characterization: Kinematisms considered to define the attitude to landslide are sliding (planar and wedge) and toppling. In both cases the rupture occur mainly along existing discontinuities and usually interest an external portion of rock mass. The possibility to landslide is directly influenced by orientation of discontinuities and of slopes and, of course, by mechanical strength of discontinuities.

Traditional geomechanical survey (ISRM, 1978) were carried out for rock slope assessment. Discontinuity properties were achieved thanks to scan-line measurements at the base of the cliff. Also some data in the medium-high portion of the cliff were available by rock climbers.

Remote sensing surveys, using a Riegl LMS-420 laser scanning system, were also done. Laser scanning is a relative new technique that gives a points cloud representing the topographic surface. An important part of the laser scanner data management is the solid modelling of the points cloud. In order to compare joints orientation from laser scanner with field surveys results, the acquired points cloud was georeferenced using 5 targets present in the laser scan windows. The integration of the points cloud with data from radiometric image (RGB) allows to obtain the so-called solid image (Bornaz and Dequal, 2003).

In this study, specific software package (Sir-IO), developed by the Politecnico di Torino, has been used to manage the solid image. The software allows a set of measurements to be directly carried out on the solid image. One of these measurements is the computation of the meanplane of a set of points. User can recognize the discontinuity directly on the solid image and can identify the discontinuity plane with a polygonal line. The software, therefore, selects all the points contained in the polygon and compute the meanplane and the respective discontinuity orientation. Data can so be plotted in stereographic projections to identify major joint sets (Fig. 2).

Description of GIS modules: *r.SMR*, *r.SSPC*, *r.wedge* and *r.fsplanar* have been developed to analyze the susceptibility to failure (Table 1). Each module is independent from the others and the calculation procedure must be repeated in order to consider all the families of discontinuity.

The *r.SMR* module is based on the geomechanical classification and uses the continuous equations introduced by (Tomás Jover *et al*., 2007). The input data are: DEM, dip and dip direction of discontinuity, the F4 index (Romana, 1993) and the RMRb index (Bieniawski, 1989). The RMRb may be introduced by a raster map or by a single numerical value representative of the whole study area. The result is a raster map showing the distribution of the Slope Mass Rating (Romana, 1993) for the analyzed system of discontinuity.

The *r.SSPC* module is based on orientation-dependent stability of the geomechanic classification Slope Stability Probability Classification (SSPC) proposed by (Hack *et al*., 2002). The input parameters are: DEM, dip direction, dip and TC (Total Condition) of discontinuity set. TC is an index that represents the joints shear strength and is the product of 4 indices defined on the basis of the characteristics of large scale and small scale roughness, infill materials and karst. Obtained raster map shows a range of values from 0-1, with values increasing with tendency to landslide.

The *r.wedgeSMR* and *r.wedgeSSPC* commands were developed to apply above mentioned methods also to wedge failure. They calculate the orientation of the line of intersection between two surfaces of discontinuity and use this value as input to analyze the tendency to slide of wedge shaped blocks. *r.fsplanar* is used to find all the pixel that satisfy the condition for planar sliding failure. For the kinematically unstable pixel, the code performs a limit equilibrium analysis method (Hoek and Bray, 1981).

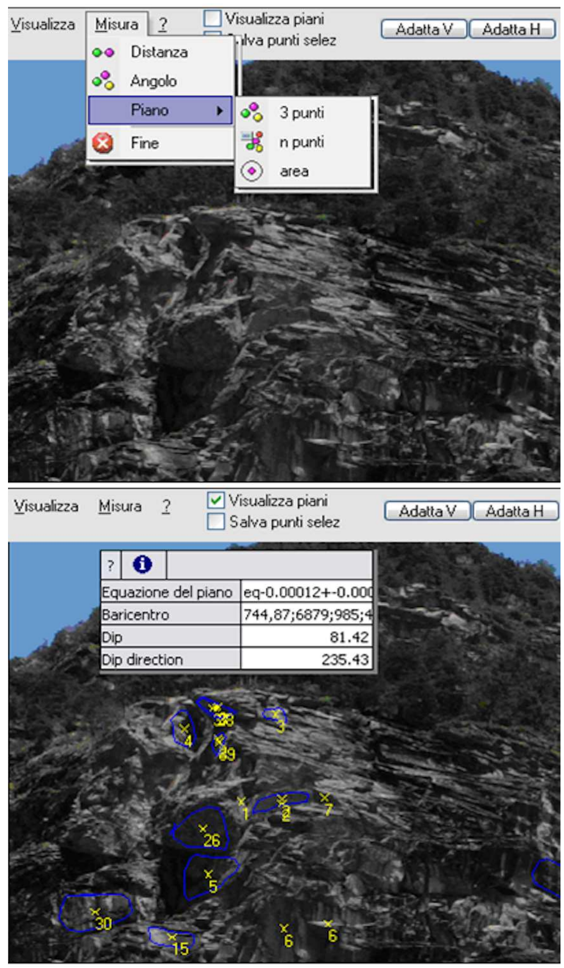

Fig. 2: Discontinuity characterization on the solid image. Dip and dip direction of every single joint can be measured on the solid image. Print screen from software package Sir-IO

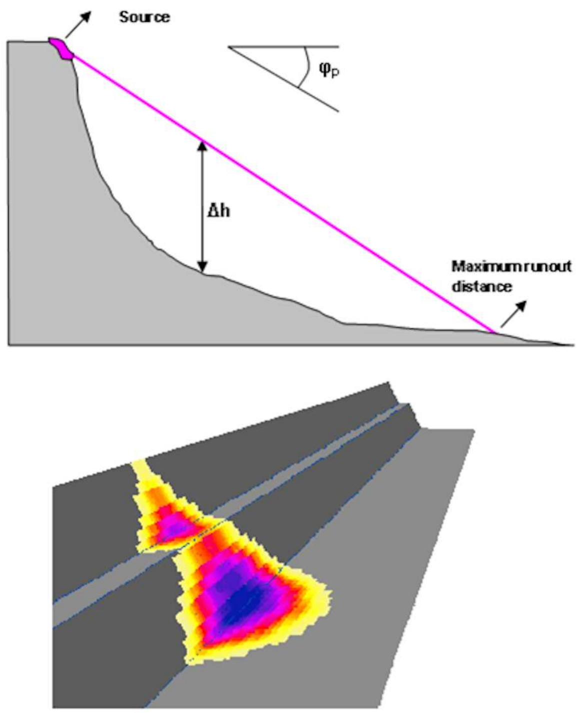

Fig. 3: Graphical representation of the shadow method. Modified after (Evans and Hungr, 1993)

Input parameters are: DEM, dip direction, dip, cohesion and friction angle of the discontinuities surface, weight volume of rock mass, height of the slope, seismic coefficient, joints percentage of saturation, highest safety factor to display.

Results of each module are raster maps that represent, for each joint set, spatial distribution of the susceptibility to landslide. They define the cinematic possibility of the failure mechanism and are based on the study of geometric relationships between the discontinuity and the slope obtained from the DEM.

Rockfall simulation: The empirical method, integrated into the *r. droka* module, was born in a two-dimensional environment and identifies the maximum area of invasion of a rockfall from morphometric analysis of the slope (Fig. 3).

The intersection between the topographic profile and the line starting from the point of detachment with a certain angle to the horizontal line defines the point of maximum propagation (Evans and Hungr, 1993; Jaboyedoff and Labiouse, 2003). The angle of inclination (φ_p) and the line of propagation are defined as zenith angle and shadow zone.

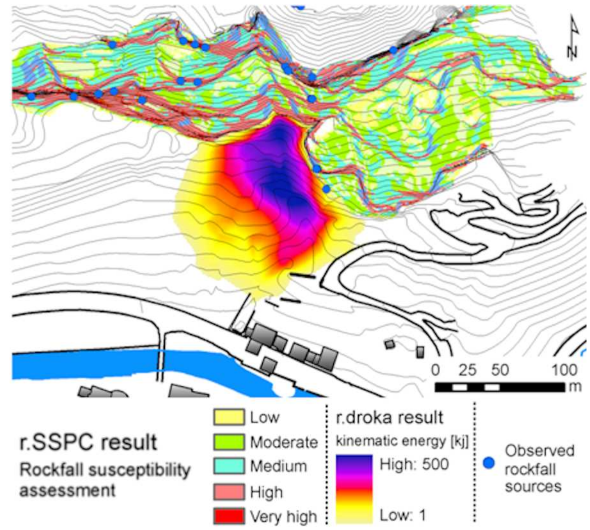

Fig. 4: An example of the landslide susceptibility map of the study area obtained from terrain failure susceptibility analysis (r.SSPC module) and runout simulation (r.droka module)

To apply *r.droka* it is necessary to know the following parameters: DEM, coordinates of the point of detachment, zenith angle (φ_p), a correction factor (f_v) which takes into account the dispersion of kinetic energy and finally the mass of the falling block. The result are two raster maps where at each pixel potentially affected by the process of falling are given, respectively, the values of kinetic energy and velocity.

The r.droka module was applied in 5 source areas characterized by high probability to landslide (Fig. 4): a φp of 35° and a fv of 0.9 were used. To test the reliability of the method, for the same source areas were carried out 2D simulations with a lumped mass code. Results were compared and highlight that r.droka tends to oversize the area of invasion and the kinetic energy associated with the rockfall too. Anyway, results are comparable.

RESULTS AND DISCUSSION

GIS modules were used for predicting rockfall hazard of an unstable cliff located above the Frontier Guard station and the Sempione highway. Both tradition field techniques than remote sensing surveys (laser scanner) were used for rock mass characterization, for identification of discontinuity sets and for DEM generation.

In the study area the solid image from laser scanner survey allowed to recognize 5 families of discontinuity, 2 more than those found thanks to traditional field surveys. The difference is in the possibility to investigate the whole cliff, rather than small parts of it due to logistical difficulties and to measure a significantly greater number of discontinuities. Measurements, direct or on the cloud of points, made it possible to identify and characterize (in volume and type of failure) 29 areas of potential rockfalls. From the points cloud obtained by terrestrial laser scanner a high resolution DEM with cell size of 50 cm was produced too. The DEM was used as basis for topographic analysis for susceptibility maps and for runout simulations. r.SMR and r.SSPC modules indicate that the planar sliding is the more recurrent failure mechanism for the cliff.

Resulting susceptibility maps are compared directly with traditional and geomorphologic observations. Results demonstrated a good agreement between the location of rockfall sources and the pixel values who indicate an high landslide susceptibility.

CONCLUSION

From a more general point of view, interesting considerations arise comparing:

- Different techniques of morphostructural surveys (geomechanical surveys, laser scanner)
- The good correspondence between the prediction of high susceptibility to landslide given by the modules and the observed rock falling path

The results of rock falling initiation, although obtained with different modules, can be qualitatively compared each other. In fact, using these modules it is possible to locate the most common mechanisms of failure and the areas with highest tendency to landslide. The maps obtained for each discontinuity and for each kinematism were overlapped each other, so to obtain a map where every cell was assigned the most critical value for stability.

Otherwise**,** the *r.droka* module provides an empirical estimate of the propagation distance based on the volume of the mass involved in rockfalls. The code does not, therefore, claim to detail the dynamics of rockfalls using ballistic or physical approaches and is, for these reasons, subject to certain limitations (Del Maschio *et al*., 2007). In particular, this research confirms the problems related to perform reliable analysis on DEM of great detail and to the tendency of oversize the area of invasion. This trend is particularly evident in lowland areas located downstream of high cliffs, like those of the study area. The main advantage is, however, the limited number of input data and the substantial convergence with results obtained by more complex analysis.

In conclusion, the studies allowed defining the type and magnitude of active phenomena in the investigated area. The quantification of energy associated with the main geomorphologic processes and the estimation of the hazard in terms of intensity and spatial distribution, were obtained. They were essential to outline the framework of the monitoring systems and of the mitigation works. The importance and economic value of social infrastructure in the valley, together with their vulnerability, require, in fact, the adoption-in this case-of many type of countermeasures, including barring actions, passive defence, consolidation of instable rock masses, but also monitoring systems to alert in situations of potential instability of significant volumes.

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