Evaluation of the susceptibility to failure of rocky slopes based on the SMR index

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ABSTRACT: In this paper, a methodology is presented for the identification of potential rockfall sources on a slope face. The methodology is based on the use of the Slope Mass Rating (SMR) index, introduced by Romana (1988). A GIS platform is used for the discretization of the slope into homogenous cells, according to their aspect and angle, and field data are collected for the calculation of SMR for each one of them. The methodology is applied at the Santa Coloma slope, in Andorra, and the obtained values, ranging from 7 to 63, with the lowest values indicating the presence of potentially unstable areas. The consistence of the results is checked by means of an index of relative rockfall density and a good correlation is found.

1 INTRODUCTION

The assessment of the susceptibility of a rocky slope to failure represents an important part of the rockfall hazard assessment. In large rock cliffs, the interest is concentrated on the identification of potential rockfall sources that could be used as an input for the trajectographic analysis. The Slope Mass Rating (SMR) index proposed by Romana (1988) combines the geometrical factors of the joints and rates them according to their contribution to the instability of the slope. The methodology presented in this paper aims at the use of the SMR for the identification of possible rockfall sources on the slope face and for the assessment of the susceptibility. It has been developed within the wider framework of quantification of the rockfall risk at the "Solá d'Andorra" slope, which is situated next to the urban area of Santa Coloma, in the Principality of Andorra. The main goal of the paper is its application on a large scale, using a Geographical Information System platform (GIS). The slope face is divided into smaller areas, called herein after cells, and their stability is evaluated separately. The importance of the obtained results is owed to the spatial information they contain. In order to check the efficiency of the methodology and whether the SMR susceptibility levels reflects properly the potential for the rock mass failure, the results have been confronted to the occurrence of past rockfall events in the slope. Finally, the consistency of the susceptibility classes is discussed using a semi-quantitative index based on the relative density of rockfalls.

2 ASSESSMENT OF THE SUSCEPTIBILITY TO FAILURE OF ROCKY SLOPES

2.1 *Description of the methodology*

The SMR index has been used for the assessment of the susceptibility of cut slopes (Irigaray et al. 2003; Budetta, 2004). The methodology that is presented in this paper has been developed for the assessment of the susceptibility to failure of natural rocky slopes with changing geometrical conditions (slope angle and aspect) and, furthermore, for the location of potentially rockfall sources.

Three main steps are involved in the methodology presented here:

i. collection of field data,
ii. discretization into cells and
iii. calculation of the SMR value for each cell, based on the RMR.

The SMR index is classified into five different susceptibility levels. Taking into account that the value of SMR is used to differentiate between susceptible and non-susceptible slope zones, it may be expected that failure would mostly appear in cells having values ranging between 0-20 (level V-very unstable) and 20-40 (level IV- unstable). Consequently, these areas can be characterized as potential rockfall sources.

The correlation of the SMR value with a probability of failure is outside the scope of this paper. However it is a prerequisite in order to proceed with the hazard analysis.

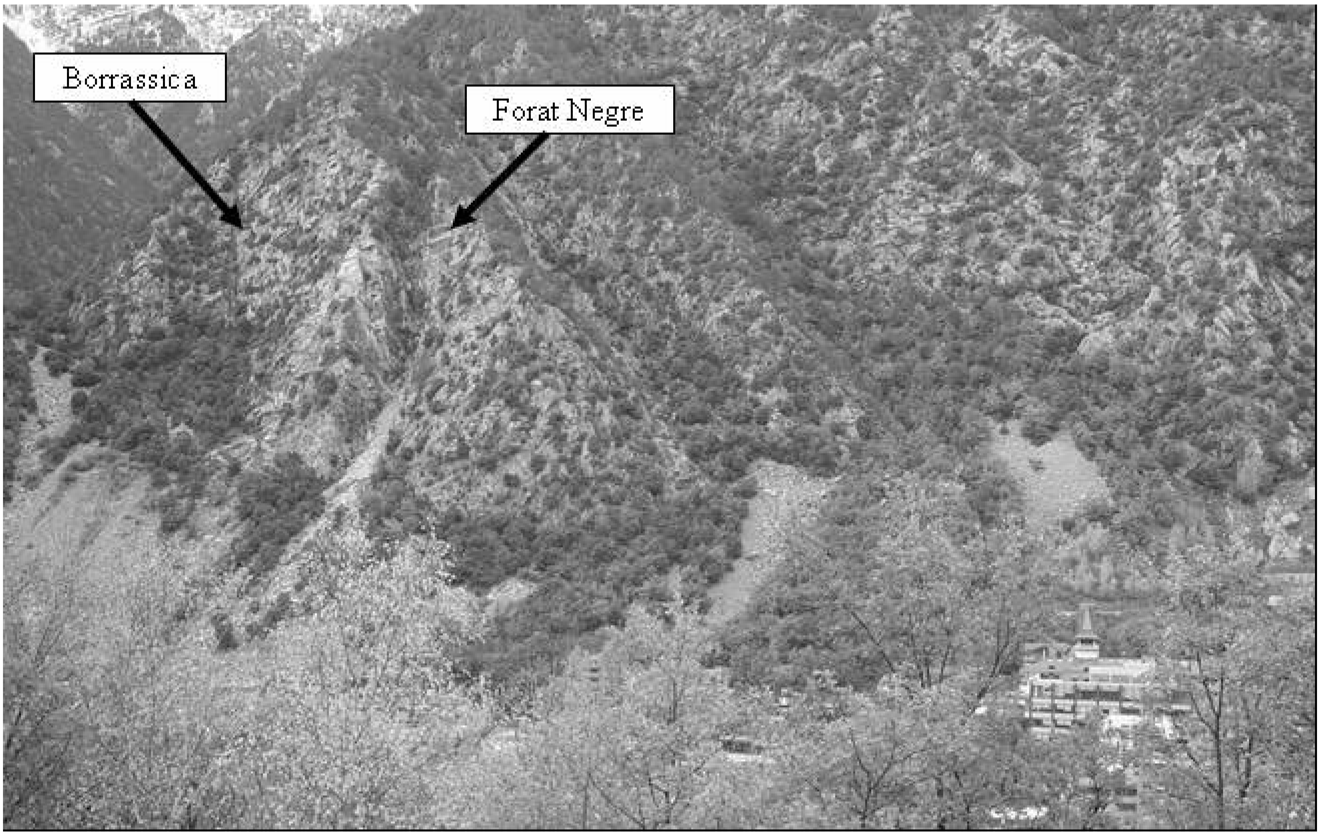

Figure 1. The Solà de Santa Coloma and location of the Borrassica and Forat Negre slopes.

2.2 Collection of field data

As afore-mentioned, the first step for the evaluation of the susceptibility of a rocky slope is the collection of field data. In this case, it involves the assessment of rock mass properties (Rock Mass Rating), as proposed by Bieniawski (1979) and the structural characteristics of the existing joint sets. During the collection of field data, it is important to define areas on the slope face, presenting homogenous structural, geo-mechanical and hydro-geological properties, given that this zoning information, will be exploited for the discretization into cells.

2.3 Discretization of the terrain into cells

Cells are areas on the slope face characterized by homogenous aspect and slope angle, rock properties as well as joint sets arrangement. The cells are drawn and graphically presented on the topographic map. In order to perform the discretization, there can be used tools provided by any GIS platform, for the superposition of the layers that contain these features and the conditionally based identification of the required zones. Average values of the aspect and of the slope angle, within the cells, have been used. The discretization is, furthermore, ruled by the assumption of a maximum height of the potential failure zone, according to which the maximum cell height is determined. For this purpose, careful site inspection is necessary for the refinement of cells, so as for them to represent potential failure zones the most realistically possible.

2.4 SMR assessment

For each cell, the value of SMR is calculated for each joint set that is present in the area. Each joint set will produce a different SMR value. The susceptibility level is, then, defined by the lowest value obtained considering all the representative joint sets. The graphical representation of the results of all the cells on the contour map or as a raster shows the spatial distribution of the SMR values along the rocky slope and allows the approximate localization of the most susceptible rockfall sources.

2.5 Validation

In order to validate the presented methodology, the consistency of the results has been checked by taking into account the number of past rockfall events. To this purpose, we have used the inventory of rockfall scars prepared by Copons (2004). The number of rockfall scars present at each cell has been counted and the consistency of the susceptibility classes has been checked by using the index of relative rockfall density, used by Baeza & Corominas (2001). This index is defined by the ratio between the density of slope failures of a given susceptibility class and the overall slope failure density. It is calculated for each susceptibility level, as given by Equation 1.

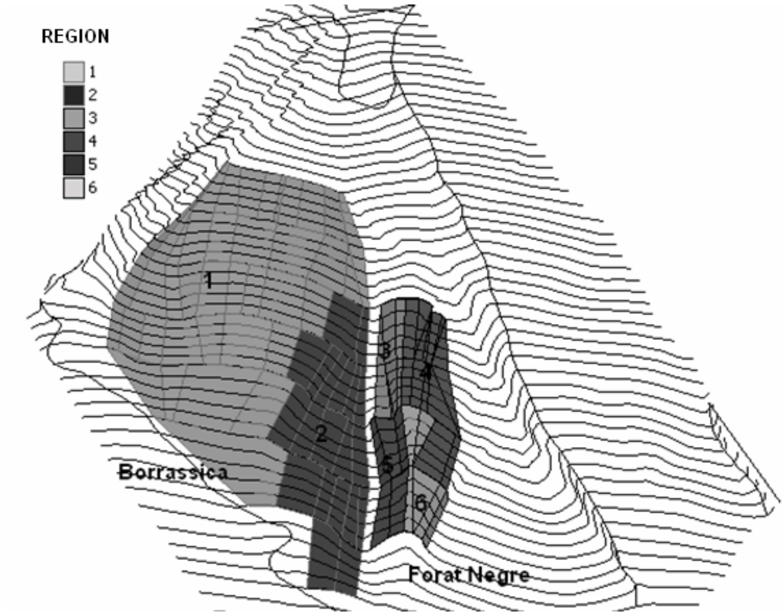

Figure 2. The location of geomechanical regions of slope of the Sola de Santa Coloma and the cells used.

$$D_{ri} = \frac{F_i / F_{tot}}{A_i / A_{tot}} \quad (1)$$

where:
F_i: number of failures in cells of susceptibility class i
F_{tot}: total number of failures
A_i: area of cells of susceptibility class i
A_{tot}: total area of cells.

Increasing values of the D_{ri} indicate higher relative rockfall frequency in the susceptibility class and decreasing values, the contrary. Obviously, for areas where there are no rockfall event data available, the validation of the methodology is not feasible.

3 APPLICATION TO THE SOLA DE SANTA COLOMA

3.1 Description of the study area

The study area is a slope situated next to the urban area of Santa Coloma, in the Principality of Andorra, located in the east-central Pyrenees.

The slope has been selected considerable rockfall activity. A great number of studies have been performed in the slope during the last years, thus allowing checking the consistency of the results. Two basins are mainly investigated, the Borrassica and the Forat Negre (Figures 1 and 2).

The retreat of the Pleistocene glaciers, about 20,000 years ago has resulted in a typical U-shape valley profile. The subsequent occurrence of morphogenetic processes such as decompression and freeze-thaw for both basins has resulted in an intense rockfall activity. In the case of the Forat Negre this is more apparent. From a lithological point of view, the affected material is mainly graniodiorite. The rock mass is very impervious and only joints close to the topographic surface, opened by stress release processes allow the rainfall to infiltrate and the subsequent increase of the cleft water pressures.

The investigated basins were divided into six main geomechanical regions, according to the rock mass properties. The regions are shown in Figure 2. Their properties, as well as the RMR value for each one are reported in Table 1.

The uniaxial compressive strength was determined directly in the rock outcrops of representative measurement stations, following the ISRM recommendations. The RQD was determined as suggested by Deere (1963). The joint spacing and condition were taken into account based on field measurements and observations. Lastly, for the groundwater conditions the most unfavourable but probable conditions have been considered. The rock mass appears intensely fractured and the main joint sets are summarized in Table 2, for each station.

3.2 Discretization into cells

A further division of each geomechanical region into cells was performed, with respect to the aspect, the slope angle, the RMR and the present joint sets. The discretization was based on the identification of areas with homogeneity with regard to these factors. A maximum height of 25 m has been considered for cells.

The aspect and the slope angle for each cell were calculated using the ArcMap toolbox. The maximum and the average slope angle values were found to be 81º and 60º, respectively.

Table 1. Rock mass properties for each station.

S	1	2	3	4	5	6
Uniaxial compressive strength (Mpa)						
	130	130	160	80	150	80
Rating*	9	9	11	7	10	7
Rock Quality Designation – RQD (%)						
	65,5	68,8	65,5	62,2	68,8	62,2
Rating*	13	13	13	12	13	12
Spacing of discontinuities (m)						
	0,25	0,23	0,19	0,26	0,23	0,15
Rating*	8	8	9	10	9	8
Condition of discontinuities (separation - mm)						
	<5	<5	<5	<5	<5	<5
Rating*	8	8	8	8	8	10
Groundwater conditions						
	dry	dry	damp	dry	damp	dry
Rating*	15	15	12	15	11	15
RMR	53	53	53	52	51	52

*Values obtained by interpolation

The distribution of the mean slope angle of the cells is presented in Figure 3, showing that the investigated slope is considerably steep.

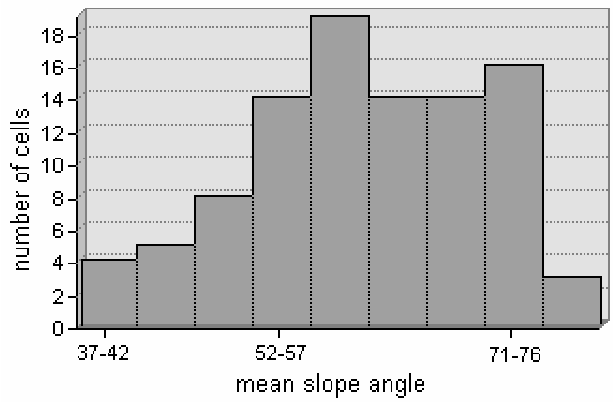

Figure 3. Distribution of the mean slope angle of the cells.

3.3 *SMR results*

The SMR value was calculated for each cell, according to Equation 2 (Romana, 1988).

$$SMR = RMR - (F_1 \times F_2 \times F_3) + F_4 \quad (2)$$

where,

F_1: reflects parallelism between the slope and the joint dip direction

F_2: refers to the joint dip in the planar mode of failure (or the intersection line for the wedge failure)

F_3: refers to the difference between the slope angle and the joint dip angle

F_4=15 (for natural slopes).

The number of cells for each susceptibility level is presented in Figure 4. The results are, also, presented graphically in Figure 5. The dark shaded areas having values of SMR lower than 40, are considered as potential rockfall sources. It can be noticed that there are many cells with low SMR, which indicates that both basins are susceptible to failure. This is in accordance with the numerous rockfall events that have occurred in the past.

Table 2. Main joint sets for geomechanical region

Station	Joint sets		
1	168,9/30	258/78	196,9/30
	56,7/51,4	315/60,5	263,8/48,1
	118,9/29,7		
2	24/68	333/70	120.3/34,8
	260,5/50	168,6/50,2	212,3/38,2
	91/43,8		
3	247/54	53,7/70,3	122,5/84,2
	206,1/46,2	329,2/10,2	
4	67/54	28,6/82,6	184,8/60,6
	221,5/77,8	322,6/47,7	303,8/30,5
	121,3/38,1	259,1/5,4	138,4/20,5
5	84/64,1	99,5/33	326,6/56,6
	124,9/79,4	204,3/21,6	42,2/18,3
	0/52		
6	280/54	81/83,5	333,2/79,9
	26,9/78,4	204,3/78	116/6,4
	151,4/72,2		

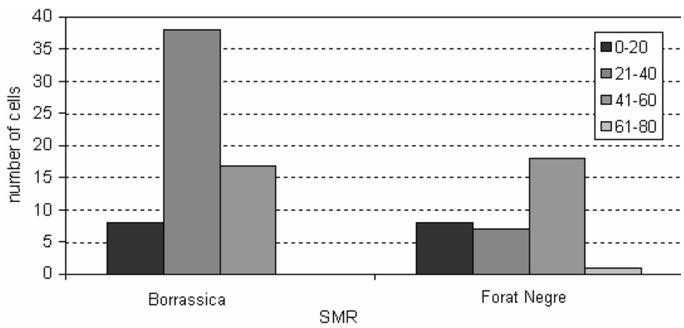

Figure 4. Number of cells for each susceptibility class.

3.4 *Validation using past events data*

As afore-mentioned, the investigated area has been chosen given the fact that past events have been very well documented, thus making feasible the validation of the results. The data used here have been collected by Copons (2004). They consist of maps with the location of rockfall scars present in the slope face as well as potentially unstable blocks (that is blocks detached from the rock mass that are prone to turn into unstable). The past and potential failures are shown in Figure 6.

The number of scars and unstable blocks has been counted for each cell and the index of relative rock fall density has been calculated for each SMR (susceptibility) class. Table 3 summarizes the results.

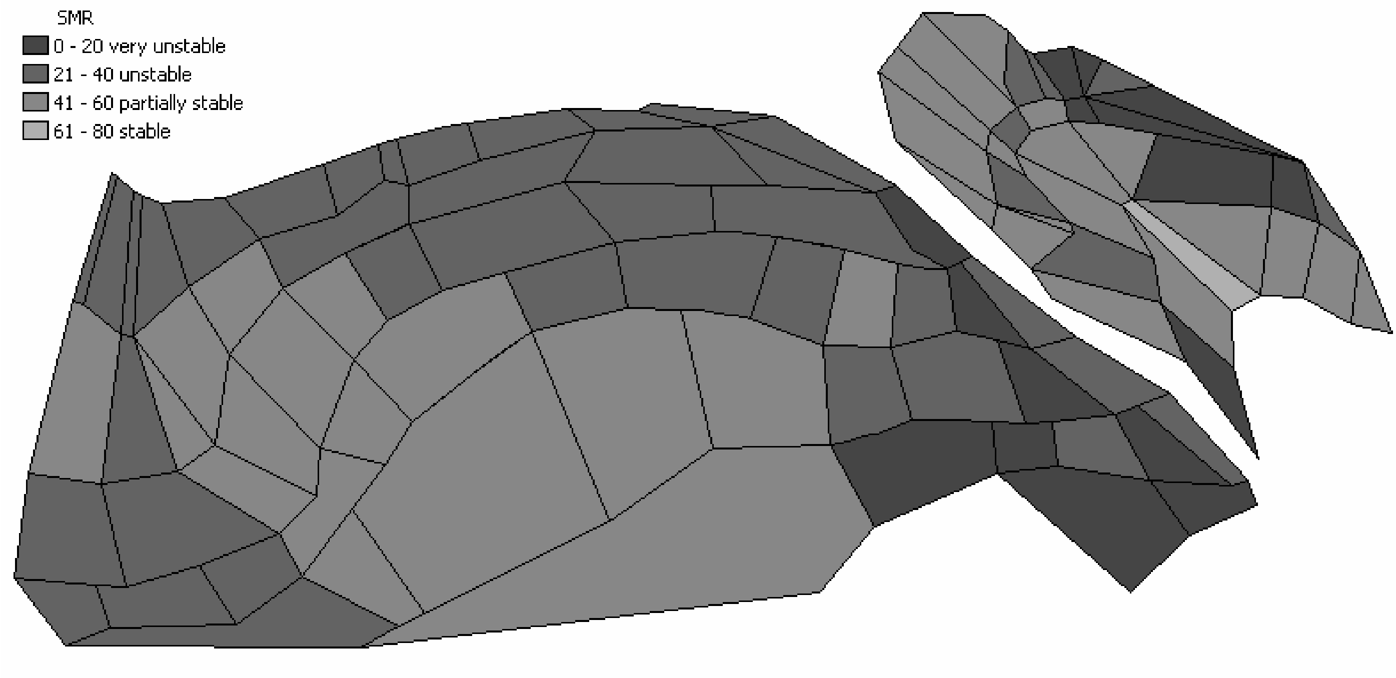

Figure 5. SMR value for each cell.

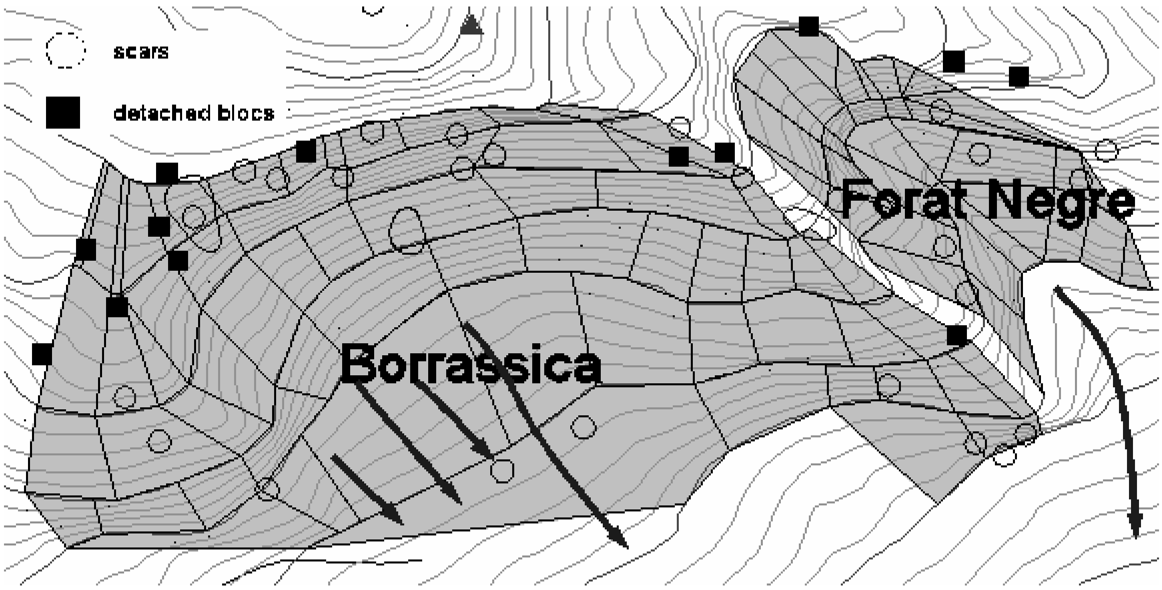

Figure 6. Past and potential rockfall indicators.

Values of the D_{ir} above 1 show that for the concerned susceptibility class, the rockfall density is greater than the equivalent average density for the total of the investigated area. The contrary is also valid. In the slope that is presented here, the D_{ir}, either considering only scars or considering the sum of scars and potentially unstable blocks, is increasing with lower values of the SMR.

As a result it may be concluded that the distribution of the observed rock slope failures is consistent with susceptibility classes obtained using the SMR. Furthermore, it can be noticed that the relative rockfall density index in the very unstable areas (SMR: 0-20) is approximately the double of the one in the case of unstable areas (SMR: 21-40), and almost 5 times more than for partially stable areas (41-60).

This ratio also reflects the relative number of rockfalls in the areas of different susceptibility.

Table 3. Verification using the D_{ir}

SMR	area (m^2)	No of scars	No of potentially unstable blocks	D_{ir}^1	D_{ir}^2
0-20	1986	7	0	2,53	2,03
21-40	6724	12	5	1,28	1,45
41-60	8432	5	1	0,43	0,42
61-80	98	0	0	0,00	0,00
Σ	17240	24	6		

[1] Considering only rockfall scars
[2] Considering scars & potentially unstable blocks

4 CONCLUSIONS

In this paper, the susceptibility of a rocky slope to failure has been investigated, using the SMR index. To this purpose a methodology has been developed and implemented on a GIS platform.

The followed steps are: i. collection of field data, ii. discretization of the area into cells and iii. calculation of the SMR value for each cell, based on the RMR index. Each of the steps has been described. The obtained results that are SMR values for the cells provide information on the location of potential failures on the topographic map, as well as the level of susceptibility for each cell. It is considered that SMR values lower that 40 indicate high potential for rock failure.

The consistency of the results has been checked using an index of relative rockfall density. For this purpose past event data, as assumed by the existent scars, as well as potential event estimations were used. The results obtained by the proposed methodology were found to be consistent with the occurrence of the past and potential rockfall events. Furthermore, the use of the relative rockfall density index may be useful for the evaluation of the relative number of rockfall events in an area of a given susceptibility, given the number of rockfall events in an area of lower susceptibility.

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