An approach to assess the detachment propensity of rockfall source areas: the Susceptibility Index to Failure (SIF)

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ABSTRACT: This paper proposes a practical approach to assess the susceptibility of rock slopes to produce rockfalls. Once identified the potential release areas, a rockfall Susceptibility Index to Failure (SIF) can be assigned to distinguish among prone areas with detachment propensity from 0 (null probability) to 1 (maximum probability). This index can be defined according to the presence and intensity of several causative factors, which were identified and scored on the basis of the scale of interest and the environment considered. Specifically, the small and the detailed scales and the mountain and coastal-marine environments were considered.
An application example is presented to illustrate the validity of the proposed approach.

Keywords: rockfall, detachment propensity, causative factors, Susceptibility Index to Failure (SIF), susceptibility maps.

1 INTRODUCTION

Rockfall hazard and risk analyses require potential release areas to be identified. Such areas, especially when small-scale studies are carried out, may present dissimilar topographic and morphologic features, which imply significantly different detachment probabilities. Several approaches have been developed in the literature to distinguish among initiation zones with different rockfall release probabilities (Abellán et al., 2006; Corominas et al., 2014; Del Río & Gracia, 2009; Frattini et al., 2008; Lambert et al., 2012). These approaches are mainly based on Terrestrial laser scanning (TLS) and photogrammetry data, and detailed kinematic analyses. However, when such information is not available these methods cannot be used. As a consequence, the analyses are carried out without taking the detachment probability of the different source areas into account, to the detriment of accuracy and consistency of the simulations performed.

This paper proposes a practical semi-quantitative approach to assess the probability of failure of potentially unstable rock blocks. A rockfall Susceptibility Index to Failure (SIF) can be assigned to distinguish among prone areas with detachment likelihood from 0 (null probability) to 1 (maximum probability), according to the presence and intensity of several predisposing/triggering factors. These factors were identified and scored on the basis of the scale of interest (small/detailed scale) and the environment considered (mountain/coastal-marine) (Napoli et al., 2023).

A case study in mountain environment at medium-large scale, 5 km of a regional road in Cogne Valley (Aosta, Italy), is presented to illustrate the validity of the proposed approach.

2 THE ROCKFALL SUSCEPTIBILITY INDEX TO FAILURE (SIF)

With the aim of defining a SIF index applicable to different scales of interest and environmental conditions, a wide literature review was conducted to select the main factors affecting the stability of rock slopes (VV.AA. 2001; Corominas et al., 2014; Del Río & Gracia, 2009; Hantz et al., 2021; Marques, 2018; MATTM-Regioni, 2018; Romana, 1993; VV.AA., 2008). The selected factors were subdivided into three tables, depending on whether they refer specifically to mountain, marine-coastal environments, or both. As shown in Figure 1: table A includes generic predisposing/triggering factors, while tables B1 and B2 are mutually exclusive, since they contain instability factors specific of mountain and marine-coastal environments, respectively. Each factor "f" was ranked (from 2 up to 5 classes), and assigned a numerical score "P", from the lowest (0) to the highest (3), according to its expected or assumed relevance in producing rockfalls. An exception is given by stabilization works (if present and considered sufficiently efficient/effective), because they can reduce the probability of detachment of unstable rock blocks and, therefore, they can be assigned a negative score (up to -1).

By evaluating the presence and intensity of such causative factors, a rockfall Susceptibility Index to Failure (SIF) can be defined and assigned to each rockfall source area, according to the following equations:

$$\text{mountain environment: SIF} = \frac{\sum(P_{f\_A}+P_{f\_B1})-\sum min(P_{f\_A}+P_{f\_B1})]}{\sum max(P_{f\_A}+P_{f\_B1})-\sum min(P_{f\_A}+P_{f\_B1})]} \quad (1)$$

$$\text{marine environment: SIF} = \frac{\sum(P_{f\_A}+P_{f\_B2})-\sum min(P_{f\_A}+P_{f\_B2})]}{\sum max(P_{f\_A}+P_{f\_B2})-\sum min(P_{f\_A}+P_{f\_B2})]} \quad (2)$$

being:

P_{f_A}: weight assigned to each factor included in Table A;

P_{f_Bi}: weight assigned to each factor included in Table B_i (B1 or B2);

$\sum min(P_{f-A} + P_{f-Bi})$ = sum of the minimum weights that can be assigned to the factors of Tables A and B1 or B2;

$\sum max(P_{f-A} + P_{f-Bi})$ = sum of the maximum weights that can be assigned to the factors of Tables A and B1 or B2.

If one or more factors cannot be evaluated (for example because of a lack of visibility of the slope) the contribution of these parameters must not be included in the calculation of the sum of the minimum and maximum weights, $\sum(P_{f-A} + P_{f-Bi})$.

PARAMETER \ WEIGHT, P	-1	-0.5	0	0.5	1	2	3
TABLE A - General							
Slope angle			<15°	15°-30°	30°-45°	45°-70°	>70°
Rock mass structural conditions*			Massive rock with no or a few discontinuities (Jn=0.5÷1)	One set of discontinuities (Jn =2÷3)	Two sets of discontinuities (Jn =4÷6)	Three sets of discontinuities, rock mass subdivided into small cubes (Jn =9÷12)	More than three sets of discontinuities, highly fractured rock mass (Jn =15÷20)
Conditions of discontinuities *			Very rough surfaces; not continuous; no separation; unweathered wall rock	Slightly rough surfaces; separation <1 mm; slightly weathered walls	Slightly rough surfaces; separation <1mm; highly weathered walls	Slickensided surfaces or gouge <5 mm thick or separation 1-5 mm; continuous	Soft gouge >5 mm thick or separation >5 mm; continuous
Stability conditions *			Stable		Partially stable	Unstable	
Fracturing degree of the rock mass **			Low		Medium	High	Very high
Expected rockfall events			Few events (1/10 years) - no rockfall scars		Occasional events (3/year)	Many events-visible rockfall scars (6/year)	Numerous and frequent events (9/year)
Precipitation			Low		Moderate	Intense	
Aggravating conditions							
Unstable blocks and/or overhanging sectors			None			Present	
Geological singularities (presence of faults, low resistance interlayers, heterogeneity, etc.)			None		Present		
Seepage/water			No/a few water seeps on slope		Numerous water seeps on slope		
Lateral or foot torrential erosion			None		Present		
Seismicity			Low		Moderate	High	
Stabilization works	Fully efficient/ effective	Partially efficient/ effective	None				
TABLE B1 - Mountain environment							
Lithology			Good quality rock			Soft rock	
Freeze–thaw cycles			None		Present		
TABLE B2 - Marine environment							
Slope orientation			Favorable (shoreline subparallel to main storm wave fronts)		Adverse (roughly shore-normal storm wave fronts)		
Elevation of the source area a.s.l.			High enough not to be affected by the erosive/unstable effects caused by waves, sea spray and tides		Not high enough to exclude erosive/unstable effects caused, even indirectly, by waves, sea spray and tides	Low enough to be affected by the erosive/unstable effects caused by waves, sea spray and tides	
Lithology and sensitivity to the erosive action of the sea			Good quality rocks (metamorphic, volcanic, etc.)		Medium quality rocks (limestones,sandstones conglomerates, etc.)	Rocks of low quality or sensitive to the marine environment	
Tidal effect			Not applicable, altitude of the source area sufficiently high	Low oscillations	Significant oscillations		
Wave energy			Not applicable, altitude of the source area sufficiently high	Moderate	High	Very high	
Cliff foot directly exposed to waves/tides			Not applicable - Protective beaches or engineering structures		No protective beaches or engineering structures		
Coastal retreat rate *			Very limited/limited		Significant		
Karst features			None		Limited	Significant	

** detailed scale only* *** medium-large scale only*

Figure 1. Parameters controlling rock blocks detachment probability: classification and relative weights. The SIF index can be obtained by combining the scores assigned to the parameters of Tables A+B1 in the case of mountain environments, or A+B2 in the case of coastal-marine environments (modified from Napoli et al. 2023).

3 THE COGNE VALLEY CASE STUDY

In order to show the validity of the approach developed in this research, the rockfall susceptibility of a stretch of about 5 km of the regional road SR47 of Cogne (Aosta, Italy) was assessed (Figure 2a). This site was chosen because of the presence of diffuse rockfalls and the availability of an instability database developed by the Valle d'Aosta Autonomous Region, which was essential to carry out a back-analysis and validate the methodology proposed. Two rockfall susceptibility analyses were carried out in the QGIS environment by means of the QPROTO plugin (Castelli et al., 2021): the former neglecting the detachment likelihood of the rock blocks, and the second considering it, by assigning a SIF index to each source point to investigate its effect on the rockfall susceptibility assessment.

3.1 Rockfall database

As shown in Figure 2a, the stretch of SR47 road considered herein has been affected by many rockfalls on both sides of the valley. In this study, only the slope facing South-West was analyzed, due to the presence of the river which, flowing West of the road in the section examined, prevents blocks that detach from the slope facing North-East hitting the SR47. The rockfall events reported in the Valle d'Aosta Autonomous Region catalogue (Figure 2a) were therefore selected by referring only to those originated from the rock slope facing South-West. From the historical data and on-site surveys, the rock block volume used to carry out the propagation analyses was assumed to be 1 m^3.

3.2 Release areas

The potential release areas were identified in QGIS by superimposing and analyzing the slope map (obtained from a 10 m x 10 m DTM) and the orthoimage, and cautiously assuming as possible sources of rock detachments the outcrops with inclinations >40° (VV.AA., 2008). Particularly weathered rocky sectors, characterized by slopes even lower than this angle, were also taken into account.

Equidistant points, representing rockfall sources, were generated within such areas and assigned the required QPROTO input parameters (Castelli et al., 2021): elevation and aspect (from the DTM), energy line angle (36° ÷ 45°), lateral spreading angle (±10°), visibility distance (800 m), boulder mass (2500 kg, assuming a rock density of 25 kg/m^3) and detachment propensity. This last QPROTO input parameter was initially assumed to be constant and equal to 1. Then, in order to highlight the differences obtained through the introduction of a detachment propensity, each source point was assigned a SIF Index (for a second Susceptibility analysis). Therefore, the presence and intensity of the causative factors listed in Tables A and B1 of Figure 1 were evaluated and ranked and Eq. (1) was used to calculate the SIF Index, which assumed values from 0.28 to 0.72, as shown in Figure 2b.

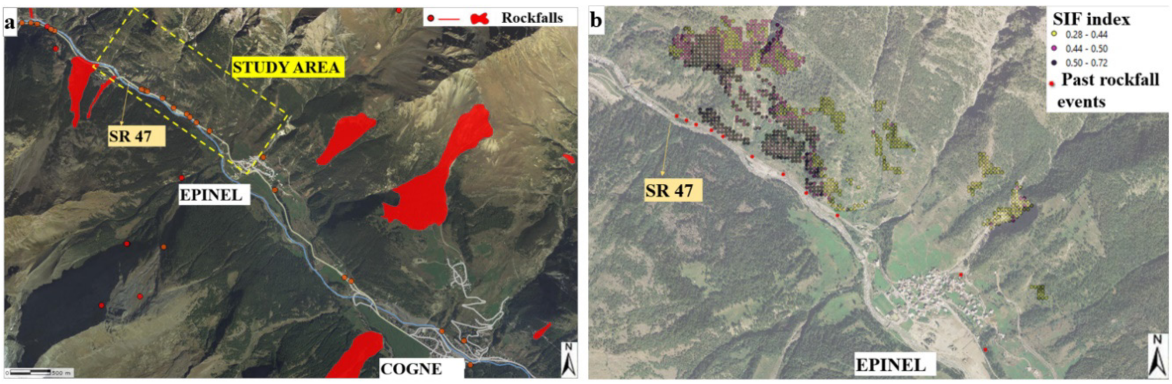

Figure 2. a) The case study area, with the indication of past rockfall events from the cartographic navigator of the Valle d'Aosta Autonomous Region; b) SIF Index values assigned to the release points.

3.3 *Rockfall susceptibility analyses*

The QPROTO plugin, based on a visibility analysis of the slope (i.e. the cone Method), was used to carry out two rockfall susceptibility analyses. Figures 3 and 4 show the susceptibility maps obtained neglecting the detachment propensity (i.e. assuming a constant and maximum SIF Index equal to 1) and assigning the calculated SIF index to each source point, respectively.

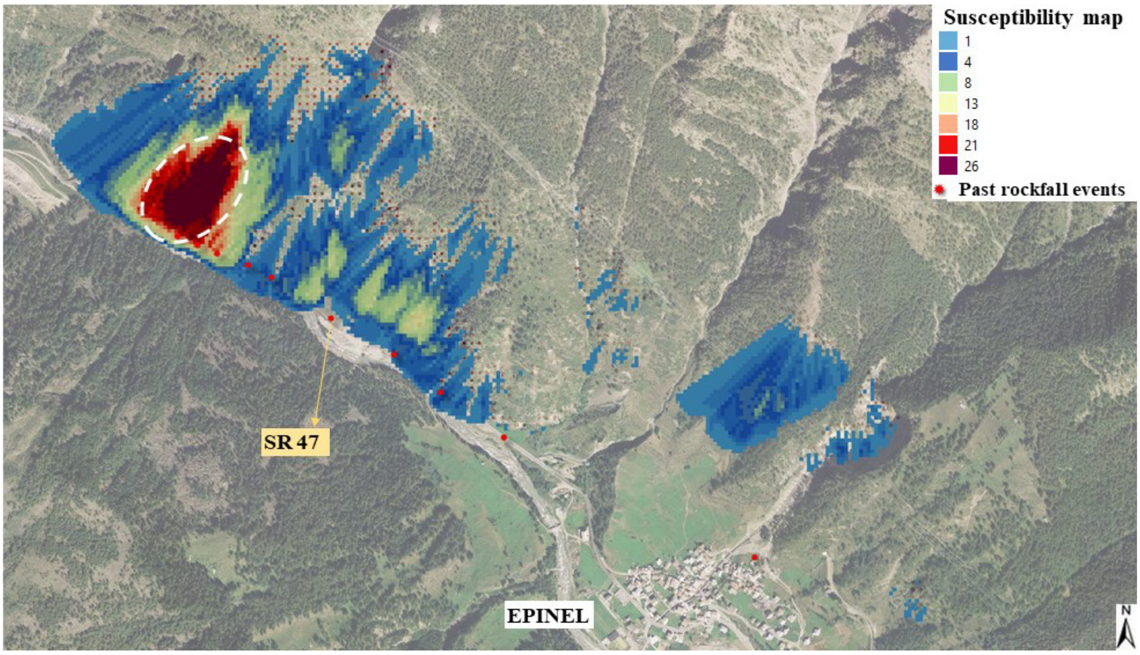

Figure 3. Susceptibility map obtained without assigning the SIF Index to the source points.

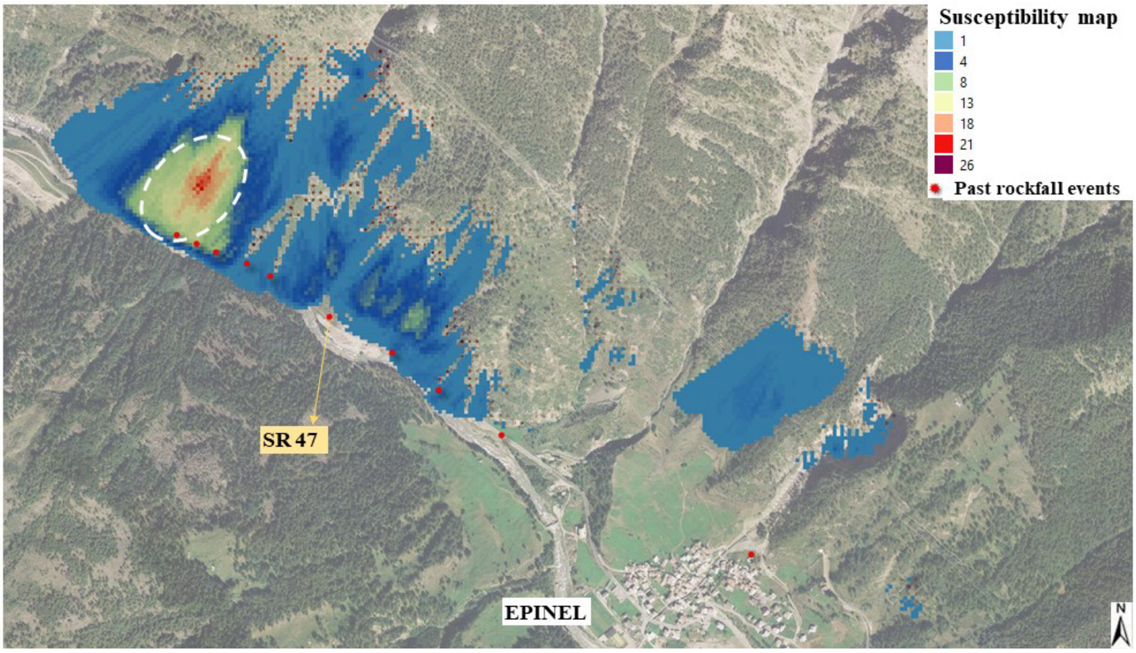

Figure 4. Susceptibility map obtained by assigning the SIF Index to the source points.

The value of the susceptibility is expressed numerically, and corresponds to the weighted passage frequency of the rock blocks (i.e., the sum of the SIF Indexes of all the source points viewing the considered DTM cell).

From the comparison of the two maps (Figures 3 and 4) it is apparent that when the SIF Index is introduced in the analysis a widespread susceptibility reduction is obtained. This is particularly evident for the area characterized by the highest susceptibility, and highlighted with the dotted white ellipses, where the assignment of a detachment likelihood to the source points produced the most significant reduction (from a value of about 26 to about 12). Such a reduction allowed for more reliable results to be obtained. In fact, the susceptibility map of Figure 4 is more consistent with the historical data recorded by the Valle d'Aosta Autonomous Region catalogue (Figure 2a).

The results obtained demonstrate, therefore, that the SIF Index allows to identify the zones most susceptible to rockfalls by differentiating invasion areas with equal passage frequencies (i.e. number of source points viewing these DTM cells) according to the actual higher proneness to instability of the corresponding release points.

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