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A semi-quantitative approach to assess the propensity of rockfall source areas to instability based on the Susceptibility Index to Failure (SIF): the case study of Capo Calavà (Italy)

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Abstract. This paper develops a practical semi-quantitative methodology to assess the probability of failure of unstable rock blocks for different environments (mountain and coastal-marine) and scales of interest (small and medium-large scales). According to the presence and intensity of several causative factors, a rockfall Susceptibility Index to Failure (SIF) can be defined and assigned to each rockfall source point so as to generate weighted frequency runout maps and, therefore, obtain more reliable rockfall hazard and risk maps.

A novel approach, implemented in a Matlab routine, is also proposed to determine the release activity of different rockfall source areas, with reference to specific elements at risk. Such information makes it possible to identify the most efficient locations for the installation of risk monitoring or mitigation systems.

The proposed methods are applied to a case study in the northern coast of Sicily, Italy, where a susceptibility analysis is carried out in the QGIS environment by means of the QPROTO plugin (QGIS Predictive ROckfall TOol).

Keywords: Rockfalls, Failure Probability, Causative Factors, Susceptibility Index to Failure, Susceptibility Maps.

1 Introduction

Rockfalls are widespread phenomena that pose significant threats to people, structure, infrastructures and the environment. They are increasingly occurring both in mountain and marine environments as a consequence of the adverse impacts of climate change and global warming.

Assessing rockfall hazard and risk implies, among the others, the location/geometry of the potentially unstable rock areas to be identified, and their failure probability to be evaluated. To this aim, the major factors affecting instability must be analyzed and quantified [1].

In this paper, a practical semi-quantitative methodology to assess the probability of detachment of unstable rock blocks is developed, resulting in a rockfall Susceptibility Index to Failure (SIF). Coastal-marine and mountain environments are considered specifically. In association with a suitable method, the SIF Index allows weighted frequency runout analyses to be carried out and, therefore, more reliable rockfall hazard and risk maps to be obtained. Moreover, in order to identify the most effective areas for the location of risk stabilization/monitoring systems, a novel approach is also proposed to detect the release activity of the rockfall source areas, with reference to specific elements at risk.

A case study is presented to show the applicability of the approaches proposed.

2 The Rockfall Susceptibility Index to Failure (SIF)

In order to assess the failure probability of potentially unstable rock blocks, the main factors responsible for their instability were selected according to a literature review [1–8]. These factors were subdivided into three tables, as shown in Figure 1: the first table (A) includes predisposing/triggering factors that can be detected in any territorial context, while the second and third tables (B1 and B2) are mutually exclusive, since they contain predisposing factors specific of mountain and marine-coastal environments, respectively. Each factor "f" was ranked into classes, to which a numerical score "P" was assigned, from the lowest (0) to the highest (3) level of susceptibility to failure. An exception is given by the presence of stabilization/protection works (if considered sufficiently efficient/effective), since they can be assigned a negative score (up to -1) to reduce the probability of detachment of unstable rock blocks.

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 point, according to the following equations:

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

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

being:

$P_{f\text{-}A}$: weight assigned to each factor included in Table A;

$P_{f\text{-}Bi}$: weight assigned to each factor included in Table B_i (B1 or B2);

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

$\sum max(P_A + P_{Bi})$ = 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 sum of the minimum and maximum weights must not take into account the contribution of these parameters.

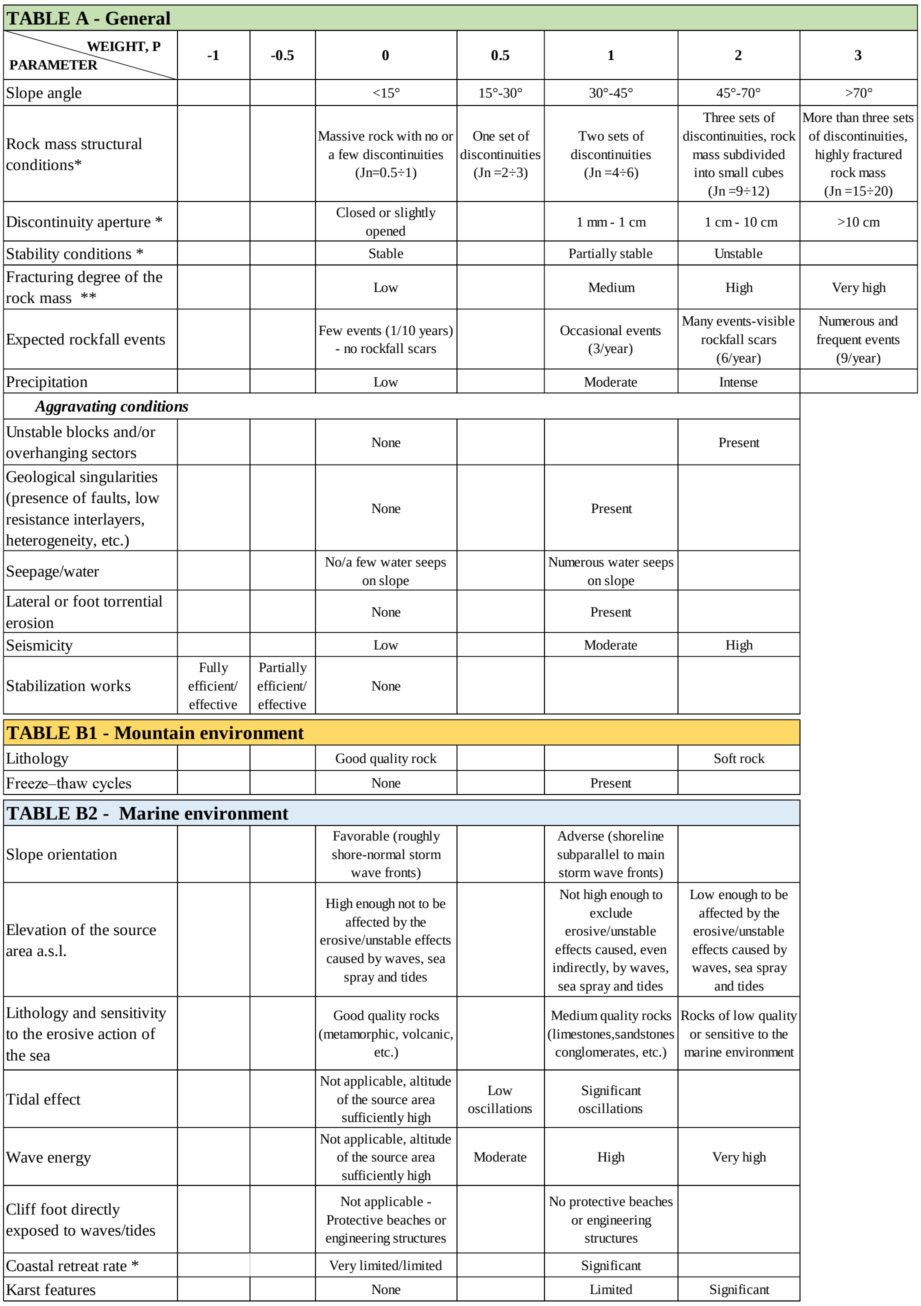

TABLE A - General							
WEIGHT, P **PARAMETER**	**-1**	**-0.5**	**0**	**0.5**	**1**	**2**	**3**
Slope angle			<15°	15°-30°	30°-45°	45°-70°	>70°
Rock mass structural conditions*			Massive rock with no or a few discontinuities (Jn=0.5÷1)	One set of discontinuities (Jn =2÷3)	Two sets of discontinuities (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)
Discontinuity aperture *			Closed or slightly opened		1 mm - 1 cm	1 cm - 10 cm	>10 cm
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 (roughly shore-normal storm wave fronts)		Adverse (shoreline subparallel to main 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*

Fig. 1. Parameters controlling rock blocks failure probability: classification and relative scores. The SIF index can be obtained by combining the weights assigned to the parameters of Tables A+B1 in the case of mountain environment, or A+B2 in the case of coastal-marine environment.

3 The case study of Capo Calavà (Italy)

Capo Calavà is a promontory located in the northern coast of Sicily, Italy. The site is formed by mica schists and phyllites (in the eastern outcrop) and plutonite (in the western outcrop), and is subjected to diffuse rockfalls. A 300 m long rockfall sheltering tunnel, net fences and draperies, were installed to protect the SS113 road (Fig. 1). Given the importance of the site and the presence of the SS113 road, this area has been chosen as a pilot site within the research project entitled “TEMI MIRATI: Critical infrastructure safety due to fast moving landslide risk”, financed with the PNR 2015-2020 (National Research Program).

Detailed survey campaigns were carried out in the last years by expert geologists and engineers, in order to (i) evaluate the rock mass structural conditions, (ii) count and measure the detached rock blocks stopped on (or close to) the tunnel and on the beach below the road, and (iii) analyze the degree of damage/deterioration of the existing mitigation structures.

The case study of Capo Calavà is presented in this paper to show an application of the SIF index and its effect on the rockfall susceptibility assessment. The propagation analysis is carried out in the QGIS environment by means of the QPROTO plugin [9].

Fig. 1. Capo Calavà site, where part of the artificial rockfall sheltering tunnel is also visible.

3.1 Characterization of the release areas

The identification of the potential release areas was performed in QGIS from a 2m x 2m DTM, on the basis of topographic and morphological features of the site. According to [7], rock outcrops showing inclinations greater than 52° were selected and mapped. Equidistant points, representing rockfall sources, were generated within such areas and assigned the required QPROTO input parameters [9]: elevation and aspect (from the

DTM), energy line angle (36° ÷ 55), lateral spreading angle (10°), visibility distance (800 m), boulder mass (440 kg ÷ 4465 kg), and detachment propensity (i.e. the SIF index, as shown in Fig. 2). To determine the mass of the rock blocks, different design volumes were first associated to the 3623 source points, according to the results of geostructural surveys and in-situ measurements of fallen blocks located on/close to the rockfall sheltering tunnel and on the beach. Then, these results were managed by means of statistical procedures, and the volumes obtained were multiplied by the rock unit weights, equal to 2343 kg/m^3 for the plutonites and to 2215 kg/m^3 for the phyllites. The energy line angle, main parameter of the runout analysis, was assessed for each source point on the basis of the analysis of slope inclination, point elevation and associated volume. Finally, the parameters of the SIF index (listed in Fig. 1) were assigned a score according to both the geostructural survey results and topographic information from the DTM. The SIF index was calculated according to equation (2), and the result obtained is shown in Fig.2.

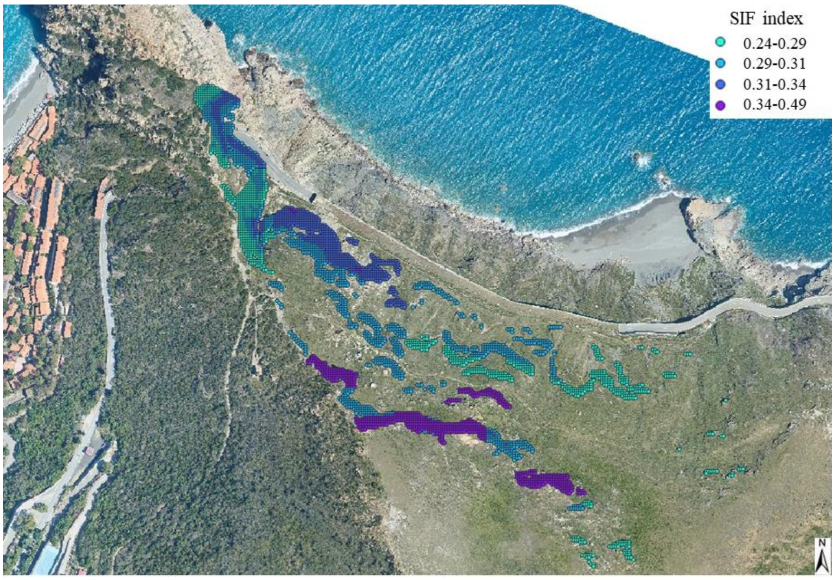

Fig. 2. Capo Calavà: SIF Index values assigned to each release point.

3.2 Susceptibility analysis results

The QPROTO plugin, based on a visibility analysis of the slope [9], was used to carry out two rockfall susceptibility analyses: the former neglecting the detachment propensity of the rock blocks (i.e. assigning a constant SIF index = 1 to all source points), and the second considering it (i.e. assigning the calculated SIF index = 0÷1 to ach source point). A calibration of the QPROTO input parameters was conducted considering the spatial arrangement of rock blocks detached in the past and accumulated along the slope, on the artificial gallery and on the beach, on the basis of the available orthophoto and on-site data survey results.

Fig. 3. and Fig. 4. show the susceptibility maps obtained with and without assigning the SIF Index to the release points.

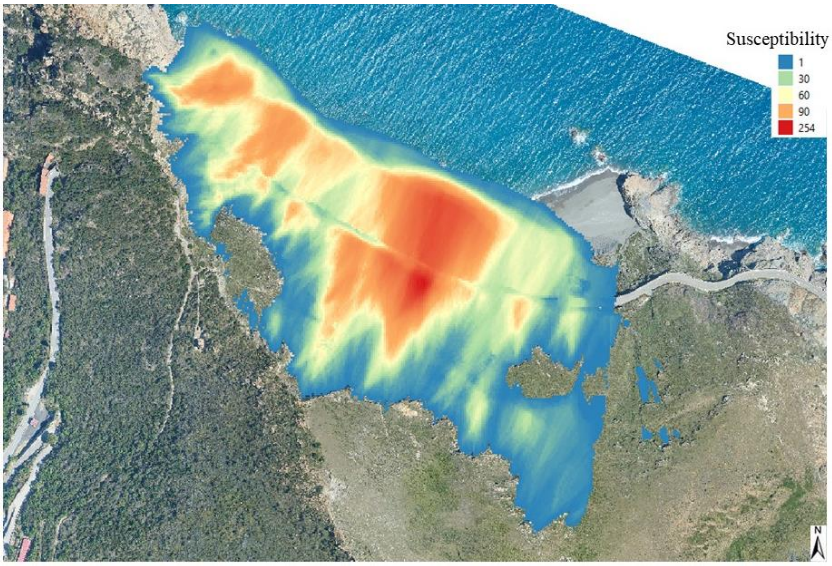

Fig. 3. Susceptibility map obtained without assigning the SIF Index to the source points.

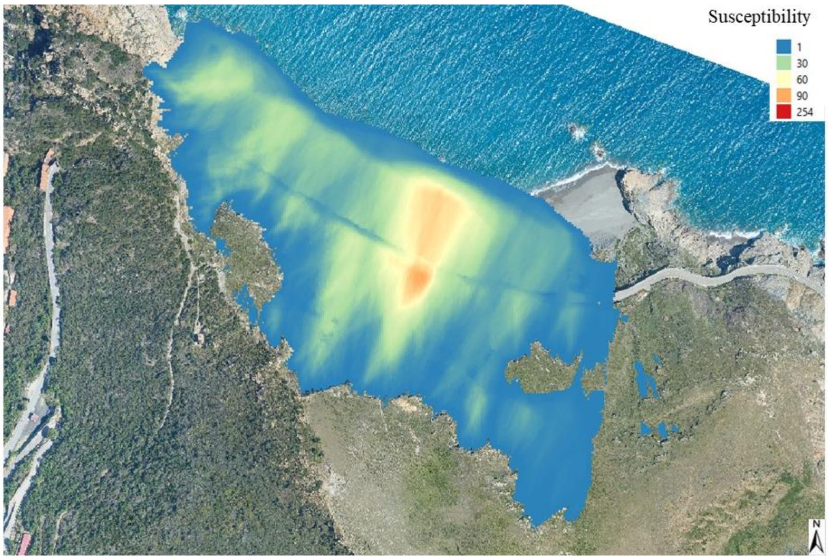

Fig. 4. Susceptibility map obtained by assigning the SIF Index to the source points.

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). By comparing the two maps, it is evident how the assignment of a detachment propensity to the different release points affects (reduces in this case) the susceptibility, allowing for more reliable results to be obtained. In fact, through the SIF index, invasion areas with equal passage frequencies (i.e. number of source points viewing these DTM cells) are differentiated on the basis of higher proneness to instability of the corresponding release points, identifying the most critical zones.

3.3 Definition of the release activity of the rockfall source areas

A novel approach is proposed that identifies, with reference to specific elements at risk, the rockfall source areas characterized by the greatest release activity (i.e. the areas from which the blocks impacting the elements at risk are most likely to detach). Such information makes it possible to identify the most efficient locations for the installation of monitoring systems on the slope (e.g. geophones, benchmarks) to mitigate the risk.

The method has been implemented in a Matlab routine: once selected the elements at risk, E_i, the code analyzes the correspondences between the rock block passing frequencies on these elements (i.e., output shapefile "Finalpoints" generated by QPROTO, [9]) and the release points. The outcome is the percentage of passing rock blocks on E_i, associated to each source point.

Fig. 5 illustrates the release activity map obtained for the Capo Calavà site, where the SS113 road represents the element at risk, E.

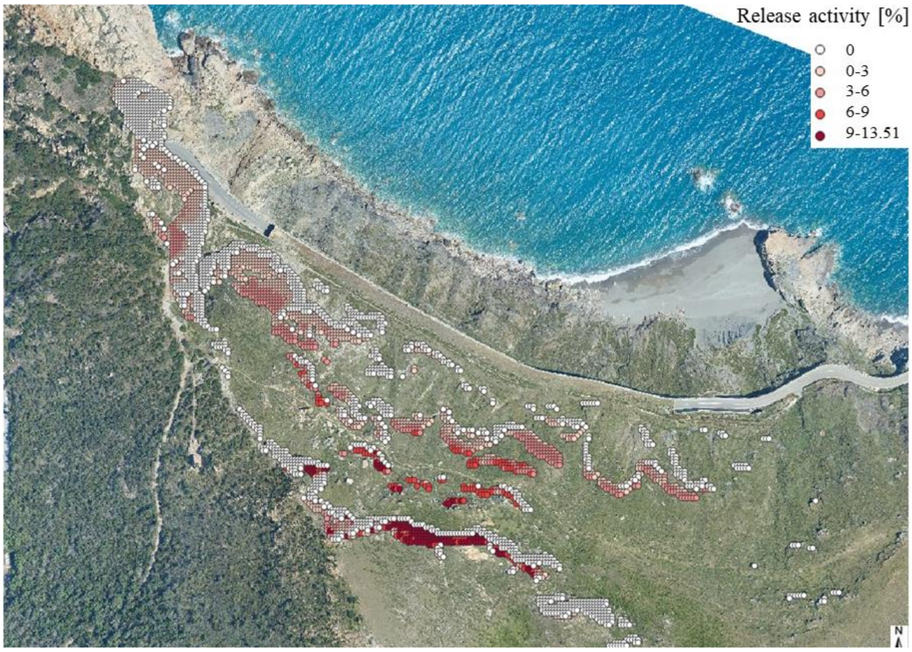

Fig. 5. Release activity of the source areas.

The result obtained indicates that 91% of the source points have a release activity lower than 6% (i.e. can hit up to 6% of the element at risk), and that the most active release area is relatively small (only 170 of the 3623 source points) and with a maximum release activity equal to 13.51%.

4 Conclusions

In this paper, a SIF index is proposed to obtain a weighted rockfall frequency runout map, and a procedure to define the release activity of the source areas with reference to a particular element at risk is set up. Both have been applied to the test site of Capo Calavà, in Sicily. According to the outcomes, geophones and benchmarks, belonging to an integrated monitoring system, were recently installed close to the most active release areas. In the future, the data provided by such monitoring system will be analyzed to further validate the approach proposed in this research.

This research was carried out under the framework of the project entitled "TEMI MIRATI: Critical infrastructure safety due to fast moving landslide risk (Project code: ARS01_00158/CUP B76C18001140005)", financed with the PNR 2015-2020 (National Research Program).

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