Validation of the rockfall SIF and SAI indexes by a 3D analysis of a rock slope in Valsesia Valley (Italy)

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Validation of the rockfall SIF and SAI indexes by a 3D analysis of a rock slope in Valsesia Valley (Italy)

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Abstract

Rockfalls are ubiquitous diffuse hazard in Sesia Valley (Northern Italy). Such instability phenomena often occur along transportation corridors and threaten local communities and tourists.

In this paper reference is made to a particular sector of the Sesia Valley, located in the municipality of Varallo (Vercelli), where in the last year a major collapse occurred and involved the road located at the bottom of the slope. After this rockfall event, several mitigation measures were planned and a great number of unstable rock blocks were removed from the slope by expert rock climbers to reduce the hazard of further rock detachments.

In this paper a 3D rockfall simulation was carried out in order to back analyze the landslide phenomenon and validate two approaches recently proposed in the literature to characterize the release areas: the Susceptibility Index to Failure (SIF) and the rockfall Source Affecting Index (SAI).

Keywords

Rockfall, 3D simulations, rockfall Susceptibility Index to Failure (SIF), rockfall Source Affecting Index (SAI)

1. Introduction

The Sesia Valley (Northern Italy, Fig. 1) is widely affected by major and periodical rockfall events. Such instability phenomena, enhanced by the peculiar geological context and adverse climatic conditions, often involve transportation corridors and threaten local communities and tourists.

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Fig. 1 Location of the Varallo case-study area, in the Valsesia Valley, Vercelli (VC), Piedmont Region, Italy.

In this paper reference is made to a limited sector of the Sesia Valley, located in the municipality of Varallo (Vercelli, VC), where in November 2023 a rock block, with volume of approximately 3 m^3, collapsed and involved the road located at the base of the slope (Fig. 2).

Fig. 2 a) detachment niche located on the Barbavara castle rock slope; b) kinzigite rock block of about 3 m^3 that detached in November 2023, hitting the road; c) road damaged by the rock collapse.

After this rockfall event, several surveys were carried out and mitigation measures have been planned, starting from the removal of a great number of unstable rock blocks performed by expert rock climbers within a week, to reduce the risk of further detachments (Fig. 3).

Fig. 3 Slope after rock removal.

The case study of the municipality of Varallo (VC) was therefore used to conduct a 3D rockfall simulation in order to back analyze the 2023 event and validate two approaches recently proposed in the literature to characterize the detachment areas.

First, runout maps were generated by means of the application of the Susceptibility Index to Failure (SIF), which allows potential rockfall release areas to be ranked according to their propensity to detachment (Napoli et al., 2023, 2024). Then, the SIF-weighted results of the propagation analyses were used to determine the rockfall Source Affecting Index (SAI), which has been developed to determine the affecting potential of the rockfall source areas concerning selected elements at risk (located within the rockfall invasion areas) (Milan et al., 2023). By assuming the elements at risk to be the road hit by the 2023 rockfall event and the buildings and related facilities located at the foot of the slope, the most critical detachment areas provided by the SAI were identified. The validation consisted in comparing the most critical detachment areas identified through the SIF-SAI indexes with those subjected to the removal of loose rock blocks on the basis of the rock climbers expertise. The 3D numerical analyses were performed using the open-source Quantum Geographic Information System (QGIS), by resorting to the QGIS Predictive Rockfall TOol (QPROTO) plugin (Castelli et al., 2021), implementing the empirical and widely used Cone Method (Jaboyedoff & Labiouse, 2011; Onofri & Candian, 1979).

2. The case study of Varallo

The municipality of Varallo is located in the north of Piedmont Region, Italy, and is affected by diffuse rockfalls, threatening human lives, structures and infrastructures, as documented by the two past rockfall events registered within the landslide inventory of Piedmont Region (Sistema Informativo Frane in Piemonte, *SIFRAP*) with Identification Numbers 2001390 and 20033600 (Fig. 4).

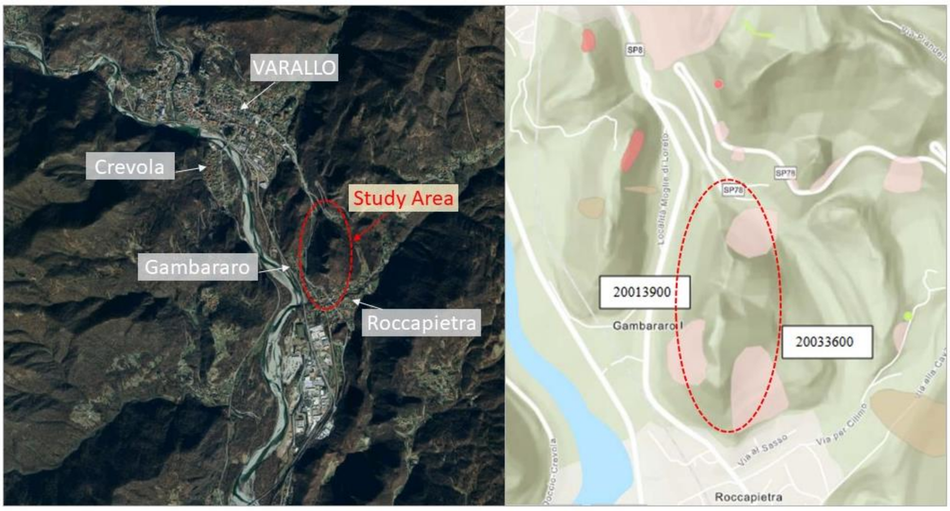

Fig. 4 Study area with indication of previous rockfall events (from SIFRAP).

The site is mainly formed by kinzigites, which are coarse-grained paragneiss, derived from clayey sediments of pre-Ordovician age, with medium-high grade Variscan metamorphism, consisting of biotite, quartz, sillimanite, cordierite, garnet, plagioclase, muscovite and K-feldspar. These rocks have experienced local processes of partial melting (anatexis), with the production of a liquid of granitic composition; the melt consolidated in situ, forming pockets and clear veins spread within the paragneiss, which thus take on the appearance of migmatites. The secondary lithology which constitutes the rock slope is the Roccapietra granite (biotite and hornblende grano-diorite), which is a local variety of the "granitic pluton". Diorites related to the Appinnitic suite of Lower Permian age (which slightly precedes the intrusion of the large granite plutons of the Laghi) are present locally.

2.1 Identification of the release areas and definition of their detachment propensity

With the aim of performing a reliable 3D rockfall analysis, several in-situ surveys were carried out in the area of interest in order to (i) evaluate the rock mass structural conditions, (ii) count and measure the detached rock blocks stopped on (or close to) the road and behind the existing net fences, and (iii) analyze the degree of damage/deterioration of the existing mitigation structures. The survey's results were fundamental in order to identify the areas were rock block detachments can occur (Fig. 5a), and characterize them through the definition of the Susceptibility Index to Failure (SIF Index). This index has been recently developed to rank, on a scale of 0-1, the potentially unstable rock areas on the basis of their detachment propensity. This parameter has been evaluated according to the presence and intensity of the major rockfall predisposing, preparatory and triggering factors, as described in Napoli et al. (2024). The SIF values obtained ranged from 0.4 (northern sector) to 0.7 (south-western sector). The result obtained is shown in Fig. 5b.

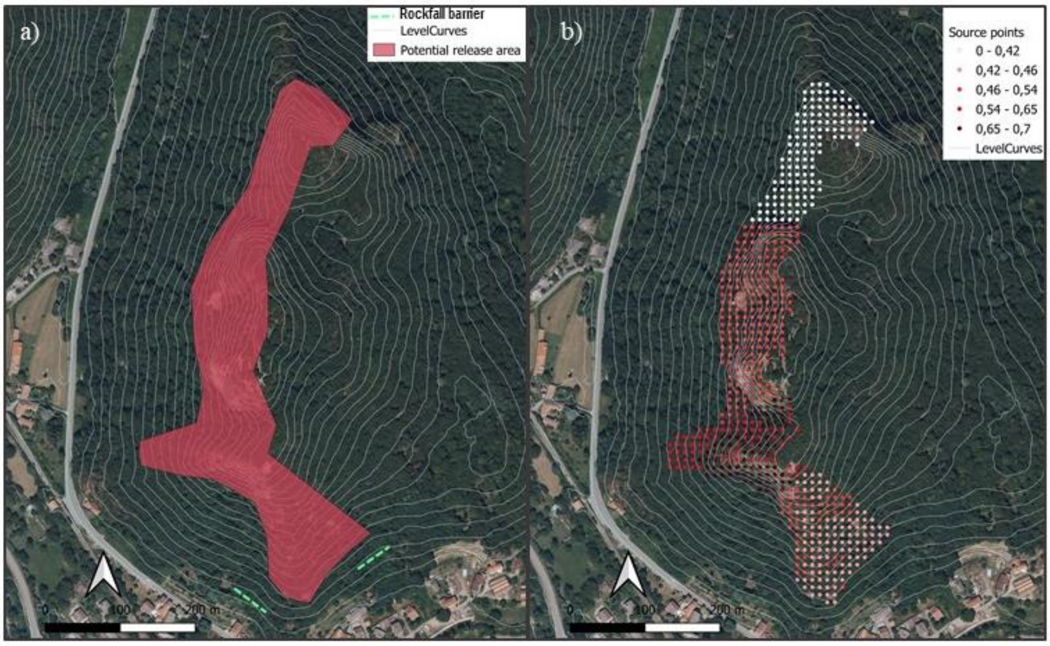

Fig. 5 a) Detachment area and existing rockfall barriers; b) Source points and corresponding SIF values.

The volume of the rock blocks was estimated by means of a statistical procedure proposed recently in the literature (De Biagi et al., 2016, 2017) on the basis of field measurements of past rockfall events (i.e. sizes of the blocks already detached and accumulated at the toe of the slope) and historical data available in the area of interest. In this regard, particularly helpful was the presence of two rockfall barriers installed in the '90s and in 2012. These structures stopped tens of blocks, which could be easily measured and used as both historical and surveyed data in the statistical approach.

By assuming a threshold volume, V_s, equal to 0.02 m^3, the parameter λ of the Poisson distribution (corresponding to the annual mean number of events greater than V_s) was 0.46, and the Generalized Pareto distribution shape (ξ), scale (σ) and location (μ) parameters were equal to 1.8074, 0.1204 and 0.02, respectively.

For a return time of 25 years the design block volume resulted equal to about 5.4 m^3.

2.2 3D run-out analysis

The rockfall simulation was carried out in the QGIS environment (vers. 3.16) by means of the QPROTO plugin, which allows rockfall runout analyses to be carried out according to a visibility analysis and the Cone Method (Jaboyedoff & Labiouse, 2011; Milan et al., 2023; Onofri & Candian, 1979).

From the release areas identified from the in-situ surveys (Fig. 5a), a set of source points was generated (Fig. 5b), from which it is assumed that rock blocks can detach.

Each source point (named "S" in Fig. 6) is associated with (the apex of) a visibility cone, geometrically defined through (i) the energy line angle, φ_p, which represents the global block–slope interaction as an equivalent friction, and (ii) the lateral spreading angle, α, which accounts for the intrinsic variability of the rock blocks trajectories (Fig. 6). These angles can be set according to the falling block volume and several slope characteristics (Castelli et al., 2021). The DTM (Digital Terrain Model) cells covered by the visibility cone constitute the area that can potentially be affected by the rockfall (i.e. by the detachment of a block identified by the source point "S").

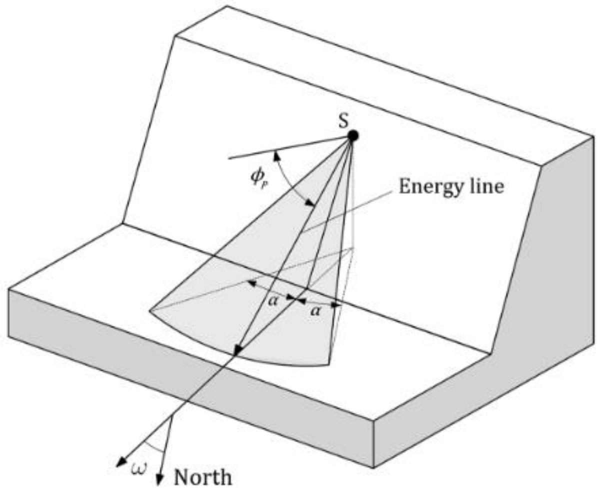

Fig. 6 Spatial definition of the visibility cone as defined in QPROTO: φ_p is the energy angle, α is the lateral angle, and ω is the dip direction (Milan et al. 2023).

For the case study of Varallo (VC), according to a preliminary calibration, the lateral spreading angle was kept constant at 10° for all the source points and the energy line angle, ϕ_p, was defined on the basis of the slope dip, point elevation and associated volume, according to Castelli et al. (2021), obtaining values in the range 30°÷38°. The other input parameters necessary in order for the QPROTO plugin to run were (i) the visibility distance, which was set at 800 m, (ii) the elevation and (iii) the aspect of the DTM cell belonging to each source point, which were derived from the DTM directly in QGIS, and (iv) the mass, which was computed from the design block volume (i.e. 5.4 m^3) by assuming a unit weight of the rock of 26 kN/m^3.

The main output of the QPROTO analysis was the SIF-weighted runout frequency (or susceptibility) map (Fig. 7). In this map, each DTM cell is associated a number corresponding to the sum of the SIF Indexes of all the source points viewing that DTM cell.

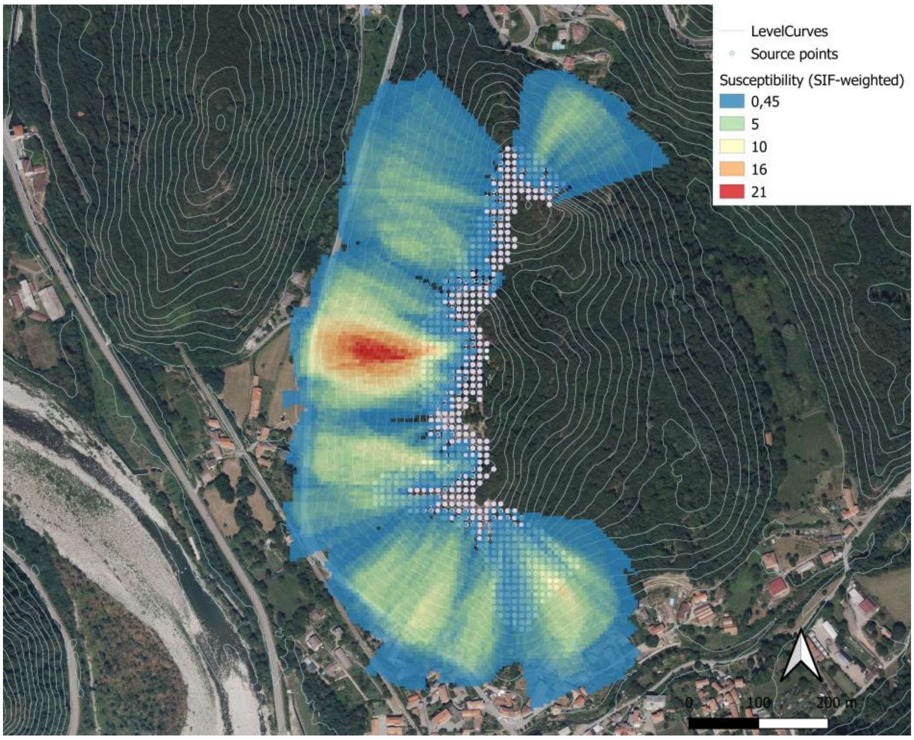

Fig. 7 - SIF-weighted runout frequency (or susceptibility) map.

The SIF-weighted map of Fig. 7 highlights the central-western zone of the study area as the most critical, followed by the southern sector. This last sector is actually the one where most of the rockfalls have been detected in the past (e.g. the event of November 2023), where rock climbers removed a great number of loose blocks in 2024, and where rockfall barriers were installed since the 90s due to the presence of many elements at risk (i.e. buildings, roads and cultivated areas).

2.3 Characterization of the release areas through the RADAR plugin

In order to identify the slope sectors where rockfalls are most likely to occur and affect specific exposed elements at risk, a ranking procedure was developed recently and implemented in a free QGIS plugin named RADAR (Rockfall Sources Influence Analysis). This plugin is based on the rockfall Source Affecting Index (SAI), and was designed to be used together with a preliminary 3D propagation analysis with QPROTO, since it takes into account the detachment propensity of the rockfall source points (i.e. SIF index) and the potential of the same source points to hit specific (user-defined) elements at risk. The result provided by this tool can be extremely useful for land planning purposes especially when large-scale rockfall analyses are carried out; in fact, higher SAI index values identify those slope sectors where to perform more detailed analyses, consolidation works, block removals, and/or install monitoring systems.

In order to run the RADAR plugin, the "finalpoints" vector file produced by QPROTO is required and the elements at risk must be identified through the definition of a polygon in QGIS. Fig. 8 illustrates the selected elements at risk (roads, buildings, parking cars and cultivated areas have been considered), while Fig. 9 shows the characterization of the source points obtained through the RADAR analysis.

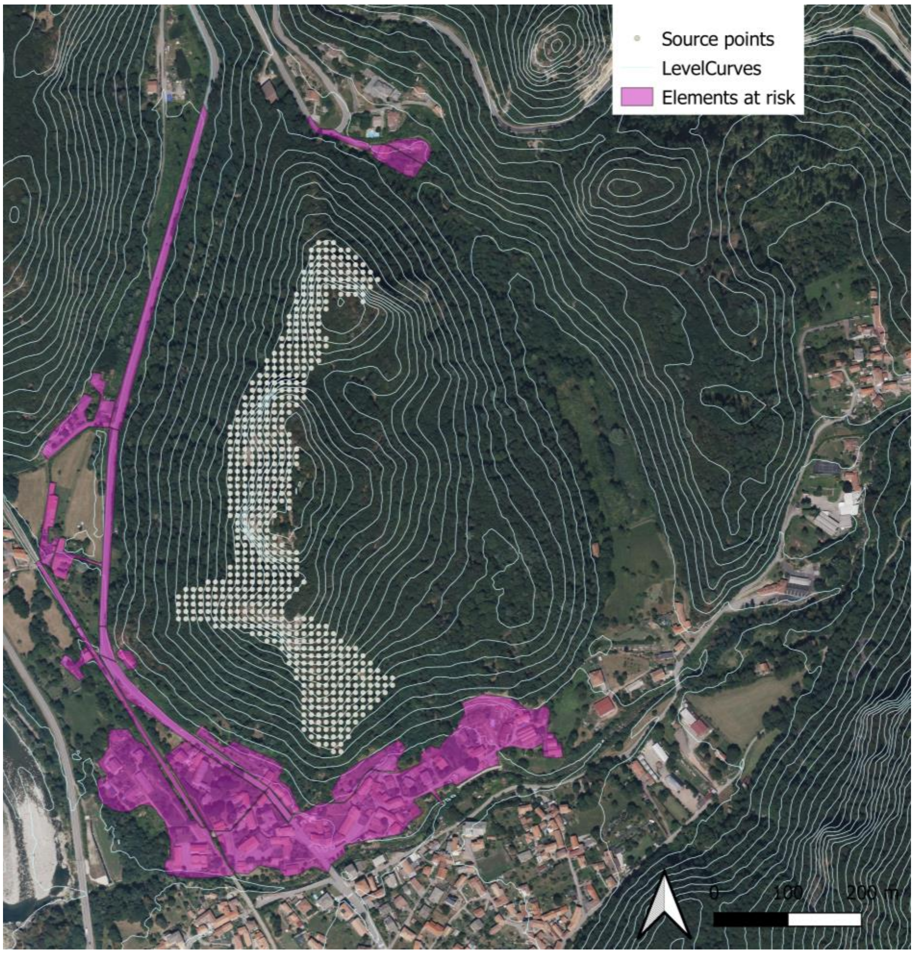

Fig. 8 Elements at risk selected for the RADAR analysis

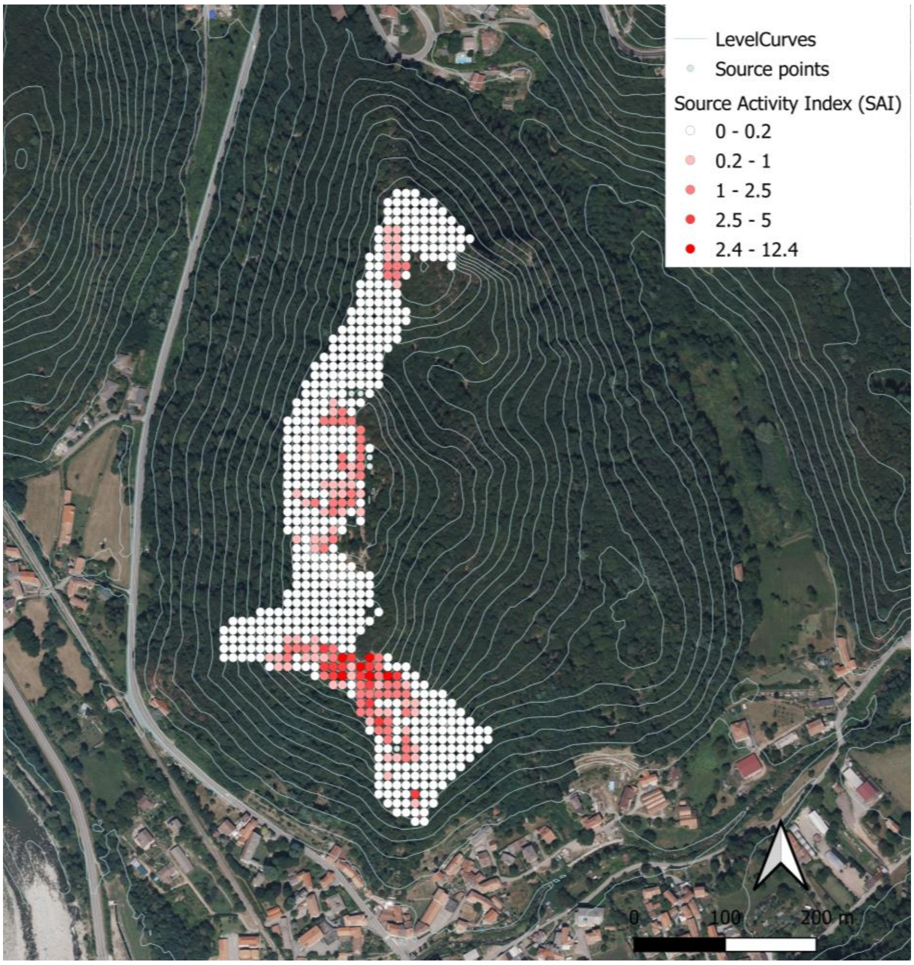

Fig. 9 - Affecting potential of the release points based on the SAI index

The result obtained indicates that 88% of the source points have a release activity lower than 1% (i.e. can hit up to 1% of the area shown in Fig. 8 and representing all potential elements at risk), and that the most active release area (i.e. SAI>2%) is relatively small (only 27 of the 627 source points) and concentrated in the southern sector, where the rock block detached in 2023 and the rock scaling intervention was performed. In this region, only 4 points present a SAI greater than 7%, and a maximum release activity equal to 12.4%.

By comparing Fig. 9 and Fig. 5b, it can also be seen that many source points with a high SIF index show much lower SAI values, due to their low probability of reaching the selected elements at risk.

3. Results and Conclusions

In this paper two novel tools, recently developed for the characterization of rockfall source areas, were applied to a case study of a rock slope subjected to frequent rockfalls, located in the north of Italy, in the municipality of Varallo (VC), in order to validate them and to highlight the usefulness of their use for managing territories affected by rockfalls,

From the results obtained, the source points with the highest SAI values basically corresponded to the sectors that the rock climbers (after a careful inspection) identified as the most critical, and where, therefore, most of the unstable rock blocks were manually removed. This outcome confirms that the novel approaches developed by Napoli et al. (2023) and Milan et al. (2024) can be extremely useful for local authorities, when limited funds are available and a selection of the most critical area must be carried out in order to design and install rockfall risk mitigation measures.

Acknowledgments

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