Rockfall susceptibility and trajectory simulations for enhanced monitoring and early warning systems along roads: the Maratea landslide case study

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INTRODUCTION AND OBJECTIVES

Rockfalls are among the most hazardous and unpredictable phenomena affecting steep slopes, especially when they threaten infrastructures such as roads and urban areas. On 30 November 2022, a major rockfall occurred at the Castrocucco cliff (Maratea, Southern Italy), severely damaging the *SS18* national road (Fig. 1). Given the urgent need for safe road reopening before the realisation of a bypass tunnel, a comprehensive susceptibility analysis and a high-resolution monitoring system were developed. This study aims to (i) reconstruct the rockfall dynamics, (ii) define the susceptible areas of the cliff, (iii) implement a site-specific monitoring and early warning system, and (iv) propose a methodological workflow applicable to similar risk-prone contexts (Santo and Massaro, 2025). Moreover, the data gathered following the rockfall major event and during the ongoing monitoring provided a remarkable dataset for future studies on rockfall processes, whose aims include:

- The simulation of rock block trajectory in static and seismic conditions for testing the efficiency of the mitigation measures;
- The definition of the coefficients of restitution of the involved dolostones formation by means of back analysis of the rockfall event;
- The investigation of the rock block deformation with the continuous monitoring system to shed light on the pre-failure deformation mechanisms and their correlation with rainfall and seismic events.

METHODS

The methodological workflow integrated drone-based photogrammetry, field geostructural surveys, kinematic analysis, and trajectory simulations. A detailed fracture dataset was collected from both field and digital surveys. Kinematic analysis was carried out on the three main slope faces using frictional parameters from analogue formations. Rockfall susceptibility was mapped by combining structural indicators with field observations. Finally, an advanced multi-sensor monitoring system was designed and installed, combining crackmeters, inclinometers, accelerometers, velocimeters, and topographic benchmarks. Rainfall data were analysed to evaluate the role of precipitation in triggering failures and to calibrate alert thresholds. Preliminary rock block trajectory simulations were run with RAMMS:ROCKFALL software (Leine et al., 2014).

ROCKFALL EVENT

The Castrocucco cliff is carved in Triassic dolostones characterised by a complex network of faults and fractures. The 2022 rockfall was triggered by intense rainfall and involved a volume of about 8000 m³ (Minervino Amodio et al., 2024), with individual blocks up to 250 m³ in volume (Fig. 2). The failure occurred along a low-angle fault plane characterised by a cataclasite layer and abundant water seepage. This geological configuration, combined with the occurrence of three main joint sets (J1: N-S, J2: E-W, J3: NE-SW, Fig. 3), predisposed the area to planar sliding and toppling failure mechanisms. The field surveys enabled the collection of further information about the discontinuities, including aperture, roughness, type of terminations, occurrence of faults, level of weathering, and presence of water (Fig. 4).

Furthermore, the comparison with previous events (e.g., 2006) highlights a progressive cliff retreat threatening cultural heritage, such as the medieval Castrocucco Castle (Fig. 5).

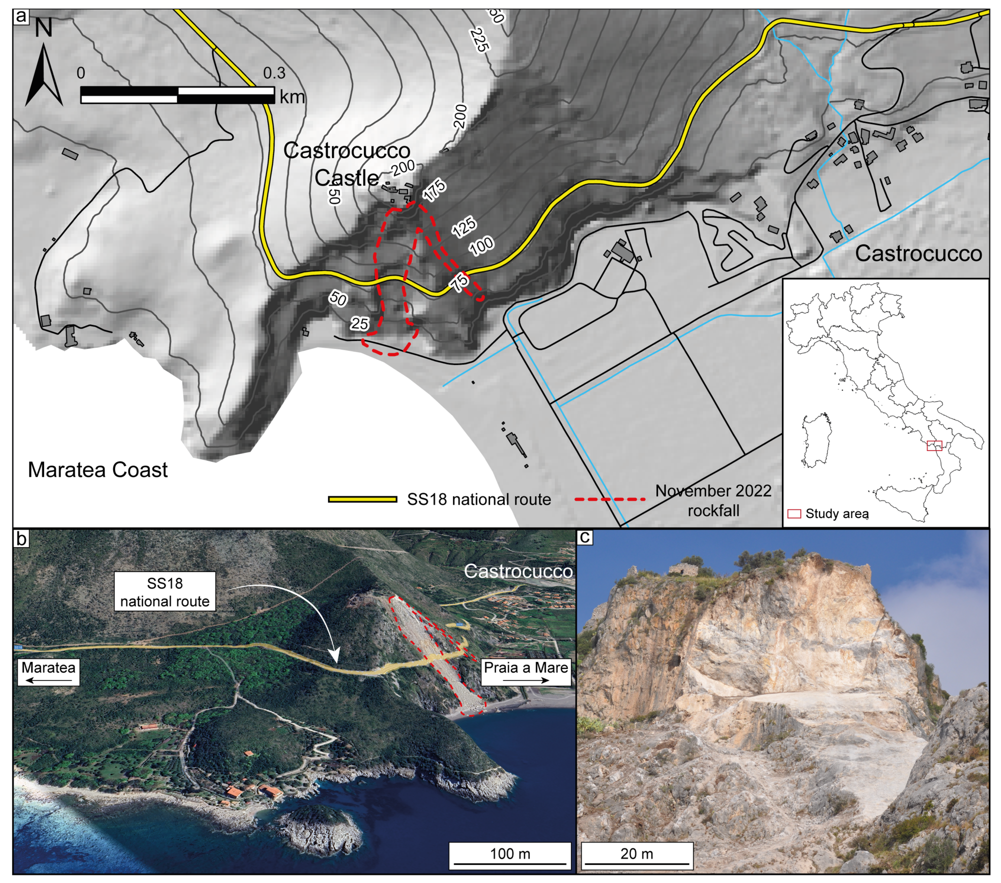

Fig. 1. a) Location of the study area highlighting the November 2022 Castrocucco rockfall trace and the SS18 national road. b) Google Earth view of the SS18 national road impacted by the rockfall event, and c) South-facing slope face of Castrocucco cliff after the November 2022 rockfall (modified after Santo and Massaro, 2025).

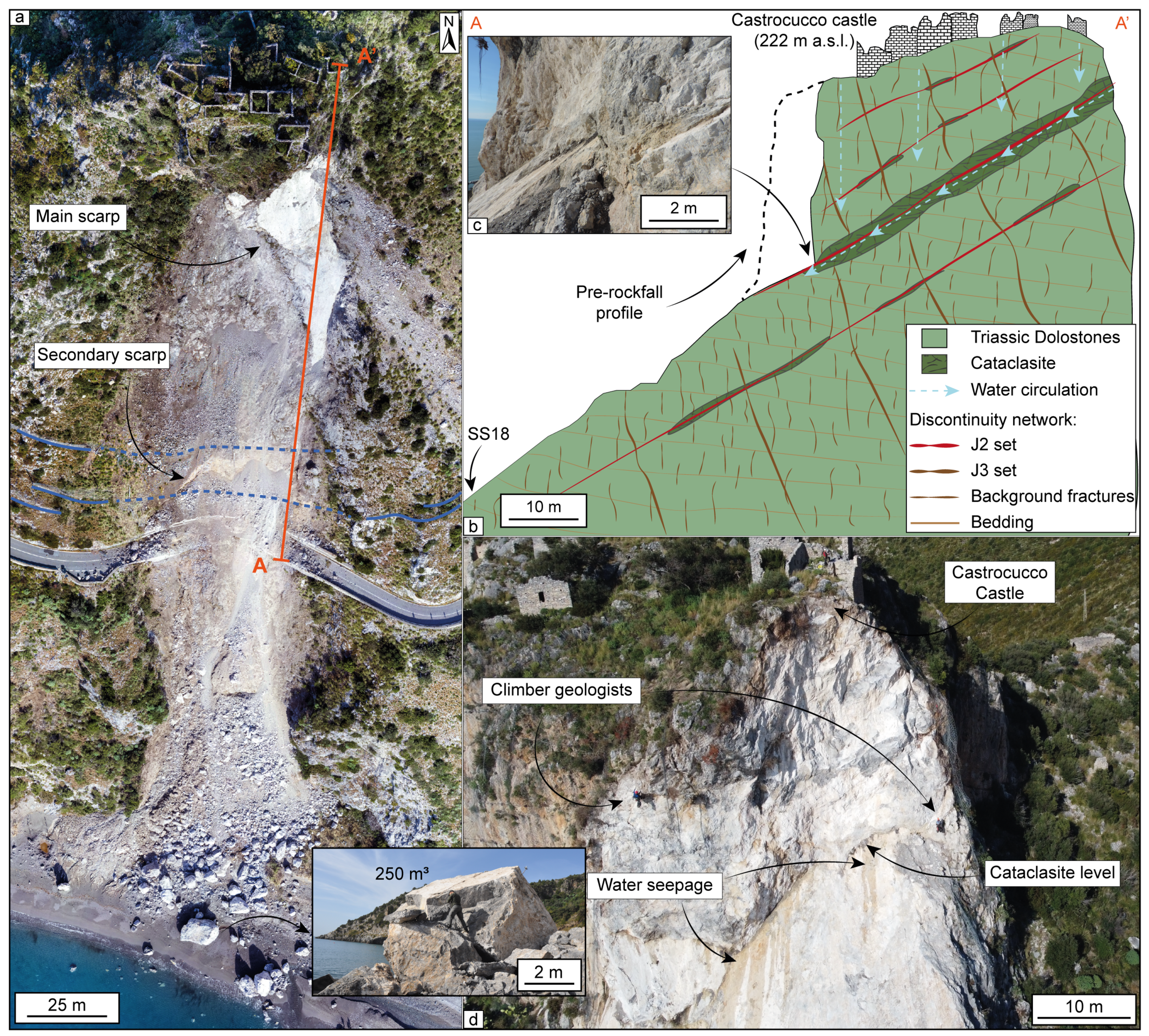

Fig. 2. a) Nadir orthoimage of the rockfall from the Castrocucco Castle to the shoreline (with a focus on one of the largest rock blocks), with the trace of the cross-section (orange A-A' line), the pre-existing protection barriers (blue lines) and the destroyed protection barriers (dashed blue lines). b) Geological cross-section of Castrocucco cliff with the rockfall scar and the reconstruction of the pre-rockfall volume. c) Detail of the cataclasite level characterising the major fault plane along which the rockfall occurred. d) Frontal drone-acquired image of the rockfall scar (Santo and Massaro, 2025).

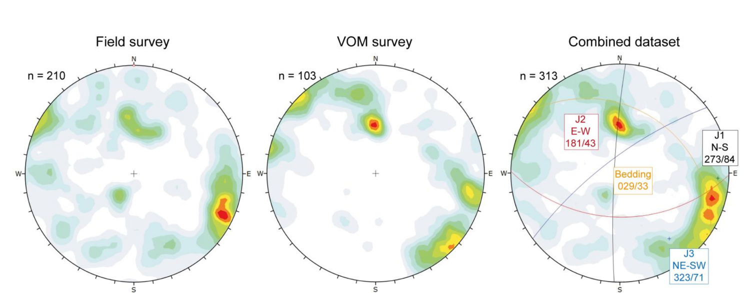

Fig. 3. Stereographic projection of the discontinuities collected from field and remote surveys and definition of the main sets (Santo and Massaro, 2025).

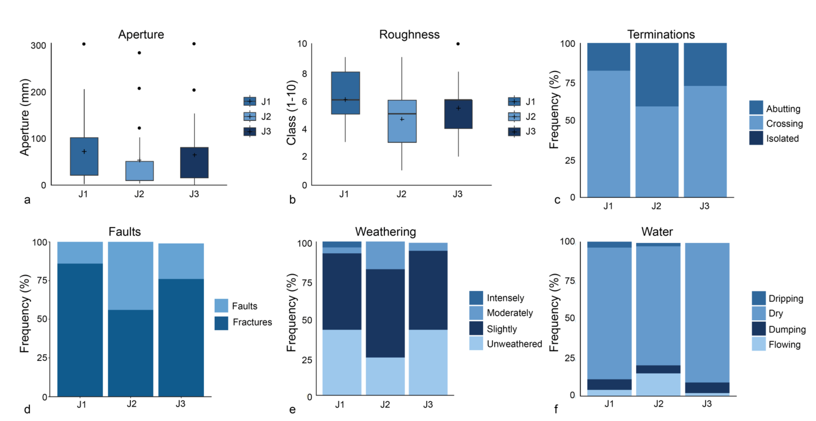

Fig. 4. Summary of the fracture properties collected on field and analysed for the three sets of discontinuities. The a) aperture (mm) and b) roughness values are presented in box-plot graphs. The data on c) terminations, d) faults occurrence, e) grade of weathering, and f) presence of water are divided in classes and represented in column charts by the percentage of occurrence in each set (modified after Santo and Massaro, 2025).

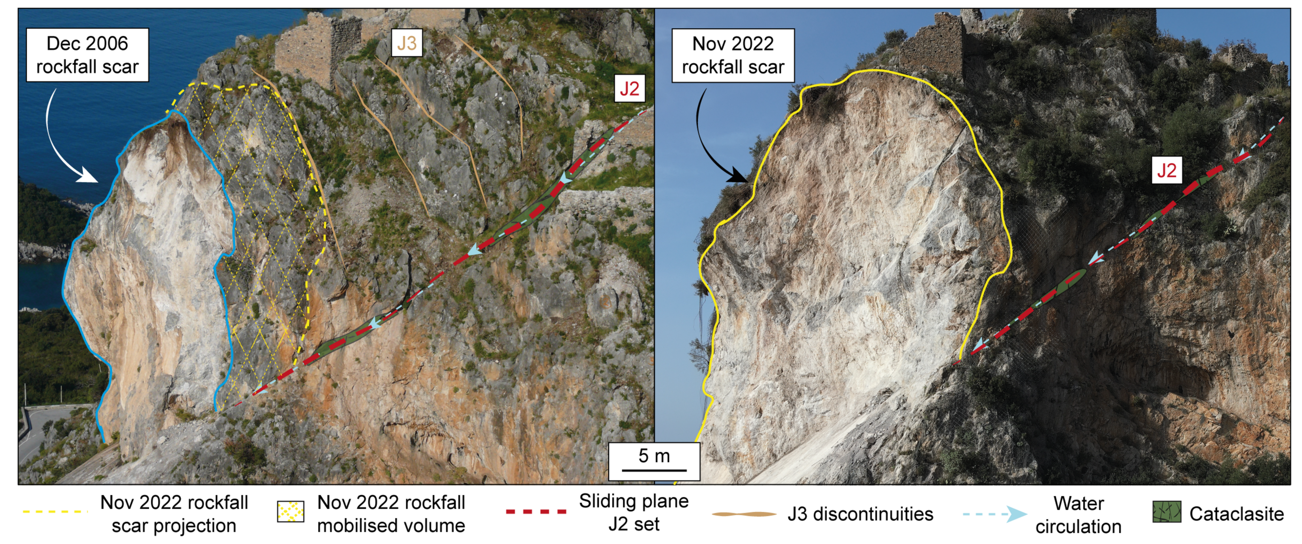

Fig. 5. Pre- and post-landslide comparison of Castrocucco cliff (December 2006 and November 2022, respectively) with structural reconstruction (Santo and Massaro, 2025).

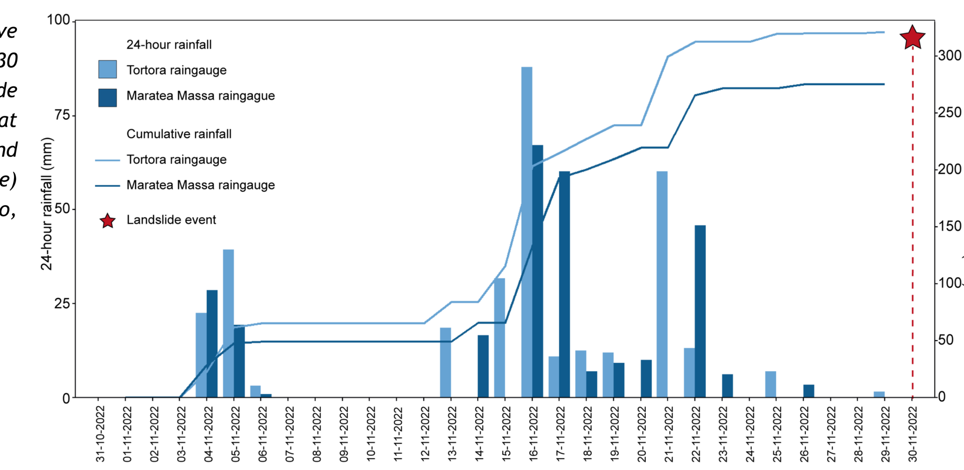

Fig. 6. 24-hour and cumulative rainfall values (mm) of the 30 days preceding the landslide event (red star), recorded at the Tortora (light blue) and Massa di Maratea (blue) raingauges (Santo and Massaro, 2025).

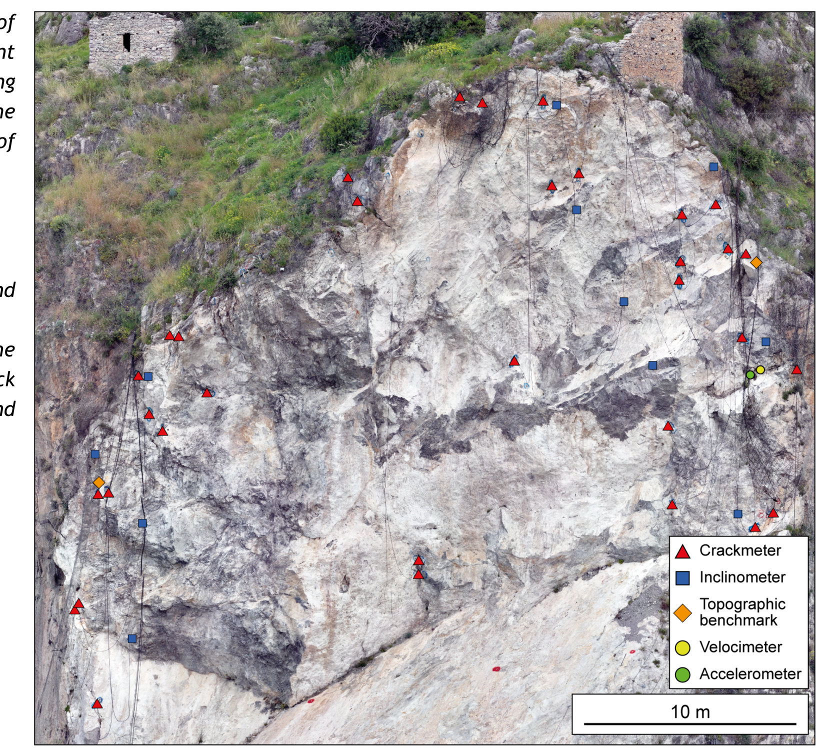

Fig. 7. Example of sensor arrangement on the South-facing slope face, with the network of inclinometers, crackmeters, topographic benchmarks, velocimeters and accelerometers disposed on the monitored rock blocks (Santo and Massaro, 2025).

ROCKFALL KINEMATICS AND MONITORING SYSTEM

The kinematic analysis defined wedge sliding and planar sliding as dominant mechanisms, especially on the South-facing slope, with more than 62% of critical intersections leading to planar sliding failure within the set J2. The latter was characterised by the highest occurrence of faults (44% of the recorded discontinuities, Fig. 4d). This aspect played a critical role in triggering the planar sliding, as the fault planes showed abundant water seepage, determined by the cataclasite developed along the fault planes (Fig. 2c, d). Additionally, rainfall data recorded more than 220 mm of rain in a 10-day period in the 3 weeks preceding the triggering of the rockfall (Fig. 6). Such a period of intense rainfall preceded the onset of the rockfall of about a week.

MONITORING SYSTEM

The geostructural investigation led the susceptibility mapping, identifying several high-risk zones near the November 2022 scar, with potential failure volumes up to 1000 m³. After the manual scaling of the most unstable blocks, a two-tier monitoring system was implemented (Fig. 7): large blocks (>10 m³) were monitored via multi-sensor setups connected to an interpreted-alert system, while medium blocks (5-10 m³) were monitored with direct alert-triggering mechanisms. This different approach was determined by the higher occurrence of pre-failure deformation for larger blocks, which enables a user interpretation of the monitoring data (Rosser et al., 2007; Royàn et al., 2014). The monitoring system, calibrated through a two-week testing period and literature benchmarks, has successfully supported the road reopening, enabling real-time traffic safety decisions during periods of heavy rainfall.

ROCK BLOCKS TRAJECTORY SIMULATIONS

The collected dataset was used to simulate the rock block trajectories in static and seismically-induced conditions. The latter was simulated after analysing the seismic site response and developing the Peak Ground Acceleration (PGA) maps (Fig. 8). The results will be used to calibrate the planning of the engineering works aimed at mitigating the hazard to the underlying SS18 road (until the bypass tunnel will be completed) and beach, as well as the medieval Castle and village of Castrocucco (IX century). Additionally, the trajectory simulations will enable the back analysis of the November 2022 event to define the coefficients of restitution of the affected dolostones (Fig. 9).

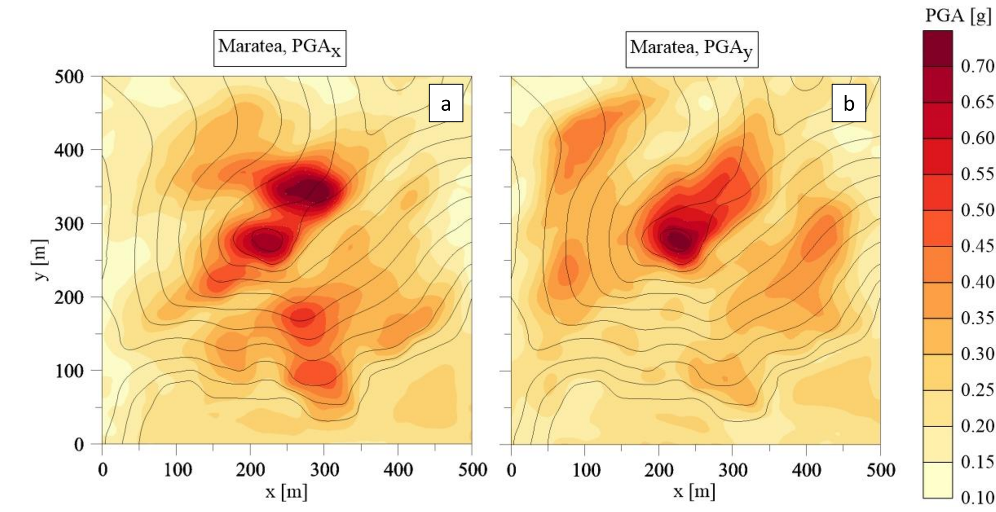

Fig. 8. Contour maps of Castrocucco cliff with values of (a) PGA_x and (b) PGA_y and the contour lines of elevation.

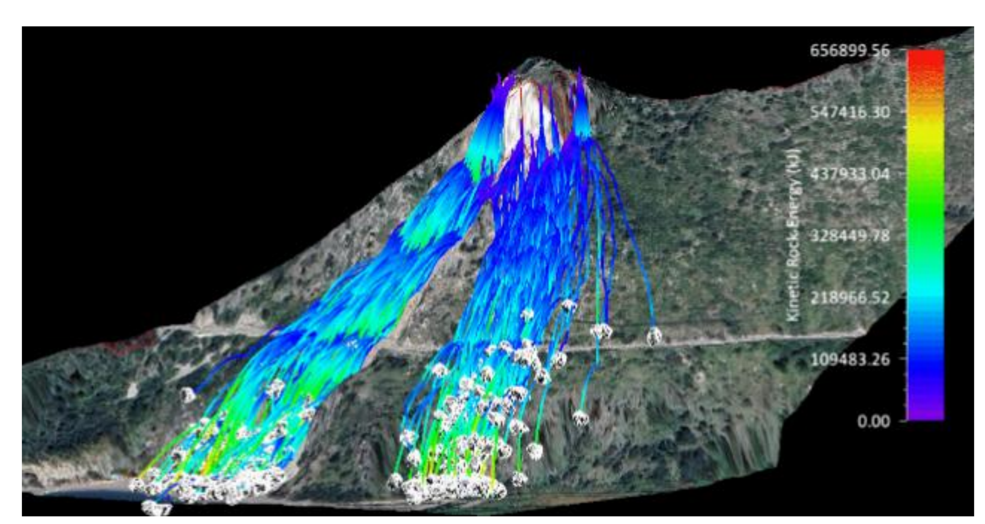

Fig. 9. Rock blocks trajectory simulations at Castrocucco cliff in RAMMS software. The colour bar shows the kinetic energy (kJ) reached by the block along their trajectory.

CONCLUSIONS

This study analysed the November 2022 Maratea major rockfall event and the consequent risk management along a critical road infrastructure, leading to the following main conclusions:

- The November 2022 rockfall event developed as a combination of planar sliding and toppling kinematics on a major fault plane characterised by the presence of a clayey cataclasite level, which concentrated the water flow along the fault surface, with consequent fluid overpressure.
- The geostructural analysis enabled the individuation of the rock blocks to be manually scaled and the definition of a susceptibility map of the cliff, which guided the focus of the following monitoring.
- The geostructural analysis defined the architecture of the monitoring system, which was developed with a multi-parametric approach and allowed the successful reopening of the road to the traffic.
- The multi-parametric monitored properties and the gathered dataset will enable future studies on the kinematics of rockfall pre-deformation failure and rock block trajectories.

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Further information

For further information about the developed monitoring system and the proposed methodological workflow check out the article Santo and Massaro, 2005.

Questions?
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