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UAV-Based Geostructural Characterization of Discontinuities in a Rock Wall to Support Rockfall Stability Analyses

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Abstract

The characterization of discontinuity networks in rock slopes is a fundamental step for assessing block-size distribution and evaluating kinematic feasibility in rockfall modelling. This study focuses on the geostructural analysis of the Groppo Sovrano cliff (Parma, Italy), a sandstone slope located in close proximity Provincial Road SP75 and affected by recurrent block detachments, which hindered the road accessibility and caused its closure. To capture the morphology of the nearly vertical and partially inaccessible rock wall, a high-resolution UAV survey combining photogrammetry and laser scanning was carried out. The integration of these datasets produced a dense, georeferenced 3D point cloud that served as the basis for a detailed structural interpretation. The main families of discontinuities were identified by extracting planar features and subsequent clustering of their orientations by defining virtual scanlines across the point cloud, in order to obtain statistically consistent measurements of discontinuity spacing. The primary objective of the investigation was to quantify block dimensions and provide useful insights for numerical rockfall modelling purposes. With the integration of remote-sensing data, discontinuity mapping, and spacing analysis, the study establishes a coherent framework for the execution of appropriate stability analyses focused on the potential detachment of rock blocks from the cliff, consequently allowing for the identification and planning of mitigation measures to protect the Provincial Road located below the rock wall.

Keywords

Rockfall, Groppo Sovrano, UAV, Discontinuities.

1. Introduction

Rockfalls are commonly defined as a type of landslide that consists of the detachment of a rock block (or several individual rocks) from a vertical or sub-vertical cliff, followed by rapid down-slope motion involving free-falling, bouncing, rolling, and sliding phases (Varnes 1978). Rockfall is the most frequent natural event in mountainous areas, threatening the surrounding environment and generating severe potential for human fatalities within its area of influence (Briones-Bitar et al. 2020). In fact, even though rockfalls have a lower level of economic risk than large-scale landslides, the high velocities associated with these events result in an extremely high risk of injury and loss of life (Ferrari et al. 2016). Therefore, rockfall-related studies, focused on hazard and risk assessment, are of great importance to prevent and reduce critical consequences and to improve disaster mitigation and preparedness capabilities (Ferrero et al. 2016; Scavia et al. 2020), usually supported by advanced monitoring system based on remote sensing and automatic data collection (Valletta et al. 2019; Giacomini et al. 2020; Segalini et al. 2023).

In this context, numerical modelling of rockfall processes represents a fundamental tool for understanding the kinematics and dynamics of falling blocks, as well as for predicting their trajectories, velocities, bounce heights, and runout distances (Li and Lan 2015). Over the last decades, several modelling approaches have been developed to reproduce the complex interaction between falling blocks and the slope surface, allowing a quantitative assessment of rockfall hazard and supporting the design of mitigation measures (Crosta et al. 2015; He et al. 2021). The reliability of these analyses, however, strongly depends on the quality of the input parameters, including slope geometry, block size and shape, and the geostructural features of the rock mass (Umili et al. 2023).

Accurate three-dimensional models of the rock wall are therefore essential for ensuring reliable numerical simulations. A detailed 3D reconstruction enables the precise characterization of discontinuity properties, which control block detachment and the definition of potentially unstable volumes, while simultaneously providing an accurate representation of slope morphology, essential for realistically simulating the phenomenon(Sun et al. 2025).In this framework, remote sensing techniques, particularly those based on Unmanned Aerial Vehicles (UAV), offer significant advantages, enabling the acquisition of high-resolution images and the generation of detailed 3D point clouds and digital surface models (Ferrero et al. 2014; Zhu et al. 2025).

2. Case study description

The Groppo Sovrano rock wall, located in the upper Bratica Valley within the municipality of Monchio delle Corti (Parma, Italy), represents a complex geomorphological setting shaped by long-lasting slope deformation processes. The area extends across elevations between roughly 930 and 1230 m a.s.l., forming a steep rock escarpment on the eastern side of the Sorgroppo ridge (Fig. 1). The present morphology reflects a combination of deep-seated gravitational movements and repeated mass-wasting events that have exposed a significant portion of the local stratigraphic sequence (Vescovi et al. 1998; Chelli and Tellini 2002).

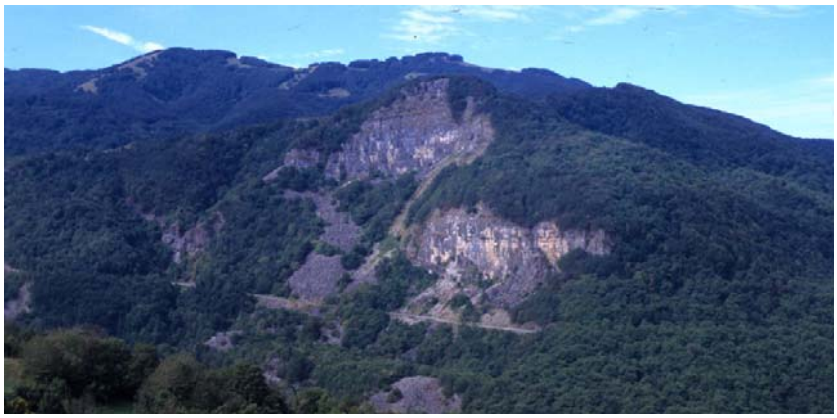


Fig. 1 Frontal view of the Groppo Sovrano rock wall (Source: ER Ambiente website).

At this site, the bedrock mainly consists of the Groppo Sovrano Sandstones, a Lower Eocene turbiditic assemblage belonging to the Ligurian Units. The formation is characterized by very thick and massive

sandstone beds, light grey in color, which alternate irregularly with thin pelitic intercalations ranging from grey to greenish and reddish tones. The sandstone layers commonly exhibit high bioclastic carbonate content, sometimes approaching half of the rock volume, and may include thin microconglomeratic horizons at their basal contacts. Because of these features, the cliff offers a clear and representative exposure of the regional geological framework (Zanzucchi 1980).

The stability of this slope is particularly relevant due to the presence of Provincial Road SP75 at its base. This road, which provides the main connection between the municipalities of Monchio and Corniglio, had to be closed on 10 December 2022 after large blocks detached from the rock wall and reached the roadway. The closure remained in force following technical inspections, as the recurrence of rockfalls makes the definition of mitigation strategies challenging. Furthermore, the upper part of the cliff hosts the only confirmed nesting site of golden eagles in the province, which designates the area as a Special Protection Zone and adds ecological constraints to any engineering intervention.

To analyze the geomechanical conditions of the slope, a detailed remote-sensing campaign was designed. Four complementary surveying techniques were employed in the investigation, each contributing a distinct layer of information to the overall geospatial framework of the study area (Valletta and Segalini 2026). Together, these methods enabled the development of an accurate, high-resolution three-dimensional model of the slope above the SP75 road near Groppo Sovrano, forming the basis for subsequent geomechanical interpretation and rockfall hazard assessment:

- Nadir UAS photogrammetry provided full coverage of the study area, achieving a Ground sampling Distance (GSD) of approximately 1.25 cm/pixel from 100 m altitude. A total of 1,019 images were collected with DJI Zenmuse P1 and DJI Mavic 3 Enterprise sensors, using 80% forward and 70% lateral overlap. Automated flight planning ensured constant altitude above ground and consistent image geometry despite complex topography.
- Oblique UAS photogrammetry complemented the nadir survey by capturing near-vertical rock faces above the SP75 corridor, enabling accurate reconstruction of cliff morphology and identification of key discontinuity sets influencing slope kinematics.
- UAV-based LiDAR scanning was crucial in vegetated areas, providing multi-return data capable of penetrating canopy cover to reconstruct the bare-earth surface. Thirteen overlapping flight lines ensured proper strip alignment, while processed/classified point clouds enabled the creation of a high-quality Digital Terrain Models (DTM).
- High-accuracy GNSS measurements established the geodetic reference frame. These data supported bundle adjustment, improving camera alignment and ensuring geometric consistency between photogrammetric and LiDAR datasets.
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All aerial acquisitions were completed on 10 July 2023, during midday hours, to ensure optimal illumination of the vertical surfaces and to minimize the presence of shadows that could degrade image interpretability. The integrated approach made it possible to characterize both the morphology of the slope and the structural framework of the rock mass, delivering a three-dimensional model suitable for the geostructural characterization of the area of interest and the subsequent rockfall trajectory modelling.

3. Results and Discussion

3.1. Identification of discontinuity sets

The primary objective of this phase was to identify and characterize the discontinuity planes that condition block detachment mechanisms and govern the overall stability of the cliff. The extraction of structural features was performed directly on the LiDAR-generated point cloud, which provided the desired density and geometric accuracy to detect even small-scale discontinuities across the exposed rock face. Planar segments were identified through clustering and surface fitting procedures, allowing the computation of orientation parameters (i.e., dip and dip direction) for each detected discontinuity. This analysis was carried out using dedicated tools for planar feature extraction and normal vector estimation integrated into the *CloudCompare* software. The selected discontinuity planes were subsequently represented in a stereonet using the *Rocscience DIPS* software, in order to define the discontinuity systems characterizing the rock mass and derive the orientation values for the mean planes. The result of this process is summarized in Fig. 2.

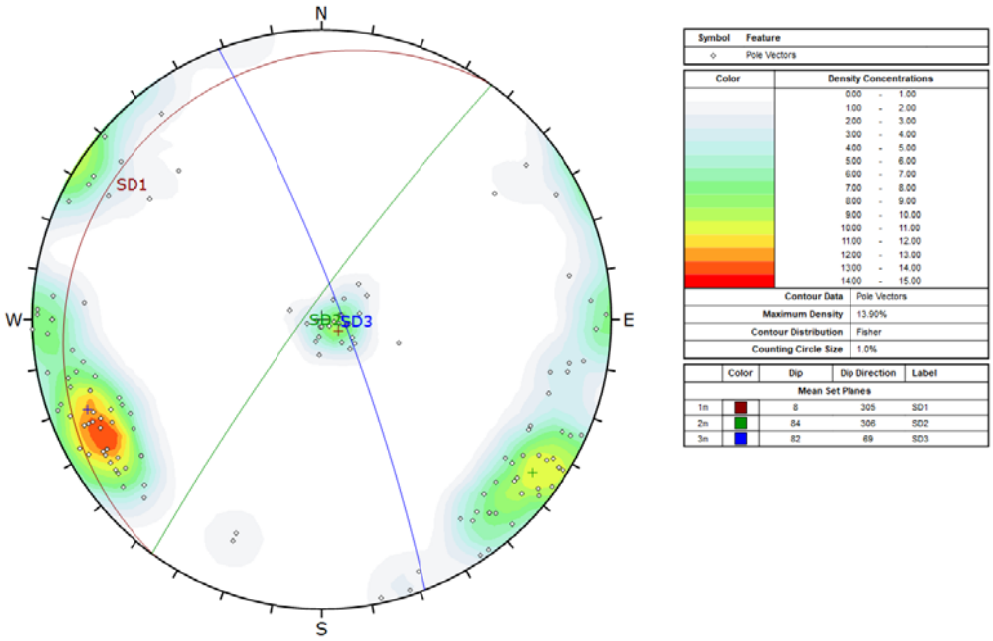


Fig. 2 Stereonet representation of the discontinuities, and related sets, identified on the point cloud.

The dataset reveals one sub-horizontal set (SD1) and two sub-vertical sets (SD2 and SD3), indicating a well-defined structural framework dominated by steeply dipping discontinuities. The combination of near-vertical planes intersecting a horizontal set may facilitate the formation of prismatic or tabular blocks, directly influencing the kinematics and likelihood of rockfall detachment.

3.2. Kinematic analysis

A kinematic analysis was performed to assess the susceptibility of the investigated rock slope to specific failure mechanisms based on the geometrical relationship between discontinuity sets and the slope face. In particular, the Markland test was applied as a rapid and effective method to evaluate the feasibility of failure modes by analyzing the spatial distribution of discontinuity plane intersections in stereographic projection.

For the case study under investigation, the analysis focused on block toppling mechanisms (direct toppling). This approach considers the position of the intersection lines between discontinuity planes with respect to the slope orientation, allowing the identification of three critical kinematic domains that define a zone corresponding to direct toppling (red area) and a zone related to oblique toppling (yellow area), as displayed in Fig. 3. The test was carried out assuming a slope face orientation of 85/127, derived from the point cloud analysis, and an internal friction angle of φ = 38°.

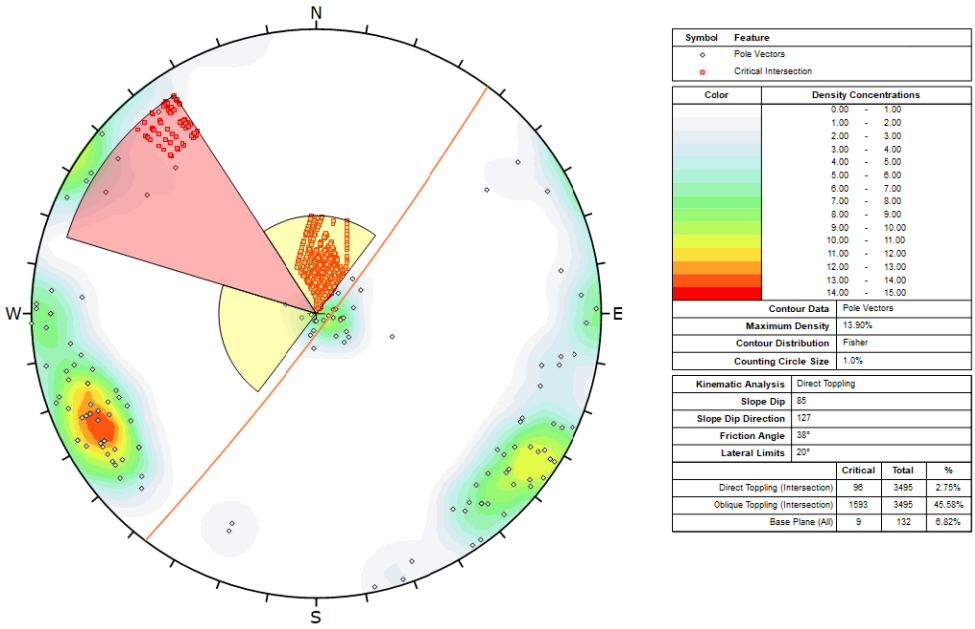


Fig. 3 Result of the kinematic analysis (Markland Test) performed on available data.

The results of the kinematic analysis indicate a significant concentration of discontinuity intersections within the oblique toppling domain, suggesting a pronounced susceptibility of the rock mass to this type of failure mechanism. Additionally, a smaller number of intersections fall within the direct toppling domain, indicating the potential occurrence of complex failure processes involving both mechanisms. The analysis highlights the dominant role of structurally controlled toppling instabilities, with oblique toppling representing the most likely failure mode in the examined slope.

3.3. Discontinuity spacing and block volume evaluation

Subsequently, scanline analyses were performed directly on the point cloud to evaluate discontinuity spacing. A set of virtual measurement transects was defined with orientations perpendicular to each of the three identified discontinuity sets, ensuring the correct assessment of apparent spacing along representative directions. The high resolution of the point cloud allowed the accurate identification of intersection points between the scanlines and the detected discontinuity planes, from which spacing values were derived. The analysis was then carried out in *DIPS* software, where progressive distances along each scanline were assigned and the integrated tools were used to compute statistically representative mean spacing values for each discontinuity set. The results of this analysis are summarized in Table 1.

Table 1 Geometrical features of the discontinuity sets identified on the rock wall.

Name	Dip/Dip direction (°)	Orientation	Mean spacing (m)	Standard deviation (m)
SD1	08/305	Sub-horizontal	1.07	0.65
SD2	84/306	Sub-vertical	1.20	0.51
SD3	82/069	Sub-vertical	1.12	0.45

Moreover, the cumulative frequency distributions of discontinuity spacing (Fig. 4) provide further insight into the variability and statistical distribution of the measured values. All three discontinuity sets show a progressive increase in cumulative frequency, indicating a relatively continuous distribution of spacing without pronounced clustering at specific values. In general, most of the spacing values for all sets fall within the range of approximately 0.5 m to 2.0 m, with cumulative frequencies exceeding 80% within this interval.

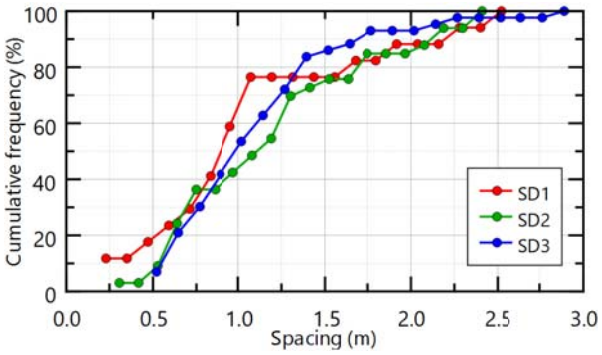


Fig. 4 Cumulative frequency of discontinuity spacing.

Based on the obtained mean spacing values, a preliminary estimation of the representative block size was carried out. Assuming a prismatic block geometry controlled by the three discontinuity sets, the average block dimensions can be obtained from the corresponding spacing values, resulting in a mean block volume of approximately 1.44 m³. In addition to the mean value, an upper-bound block size can be defined using the 90th percentile (P90) of the spacing distribution. The P90 represents the value below which 90% of the observed data fall and can be considered a realistic yet conservative estimate of extreme conditions. In this study, the combined variability of the three discontinuity sets was accounted for by assuming a lognormal distribution of spacing. Under this assumption, the P90 block volume is approximately 2.90 m³. These volumetric values provide a first-order quantitative constraint for subsequent rockfall simulations and energy-based hazard assessments.

4. Conclusions

This study presented an integrated workflow for the geostructural characterization of the Groppo Sovrano rock slope (Parma, Italy) to support rockfall stability analyses, combining UAV-based photogrammetry and point cloud processing. The adopted approach enabled the generation of a high-resolution 3D model of the rock wall, overcoming the limitations of conventional field surveys in

steep and inaccessible areas.The selected case study represents a representative example of a structurally controlled rock slope in a mountainous environment, where rockfall processes pose a significant hazard to the surrounding area, thus providing a meaningful context for testing and validating the proposed methodology.

The extraction of discontinuity planes directly from the point cloud allowed the identification of three main sets, including one sub-horizontal (SD1) and two sub-vertical (SD2 and SD3), defining the structural framework of the rock mass. The kinematic analysis, based on the Markland test, highlighted a marked susceptibility of the slope to structurally controlled instabilities, with failure modes associated with both oblique and direct toppling. Finally, spacing analysis performed through virtual scanlines and processed with appropriate tools provided representative mean values for each set, supporting a preliminary estimation of spacing frequency and block dimensions.

Overall, the results confirm the importance of accurate 3D models for the reliable characterization of discontinuities and slope geometry, which are essential inputs for rockfall simulations. The integration of UAV data with dedicated analysis tools represents an effective and reproducible approach for improving hazard assessment and supporting the development of mitigation strategies.

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