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# DIGITAL TWIN BASED FRAMEWORK FOR ROCKFALL HAZARD ASSESSMENT: REMOTE ANALYSIS OF AN URBAN CLIFF IN PALERMO (ITALY)

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## EXTENDED ABSTRACT

L'implementazione dell'approccio metodologico basato sul "*Digital Twin*", ovvero la creazione di un gemello digitale, applicata all'ammasso roccioso di Monte Pellegrino, nel suo versante orientale che sovrasta l'area del cimitero Monumentale di Santa Maria dei Rotoli della Città di Palermo, ha permesso la valutazione di alcuni dei parametri necessari alla caratterizzazione del rischio da crollo. L'indagine si è fondata primariamente sull'acquisizione di dati tramite *Laser Scanner Terrestre* (TLS), una scelta strategica che ha permesso di superare le limitazioni imposte dall'impossibilità di accesso diretto alla parete rocciosa e garantire la generazione di un dataset denso e accurato. L'elaborazione e l'analisi della nuvola di punti ad alta definizione ottenuta dal rilievo hanno permesso la segmentazione dettagliata dell'ammasso roccioso attraverso la suddivisione di questo in zone omogenee (Zn1, Zn2 e Zn3) e l'applicazione sinergica di algoritmi avanzati implementati nel software *Discontinuity Set Extractor* (DSE). Tale approccio ha permesso la definizione di un processo rapido ed efficiente, utile all'estrazione semi-automatica delle orientazioni dei sistemi di discontinuità per la definizione dell'assetto strutturale dell'ammasso roccioso. L'analisi morfologica delle zone omogenee individua per Zn2 un assetto geometrico prevalente a strapiombo. Atteso che una definizione deterministica e puntuale delle modalità di rottura richieda, inevitabilmente, ulteriori e più specifiche verifiche di stabilità che esulano da questa fase preliminare, questa prima rilevazione dell'assetto geometrico permette un'analisi preliminare delle zone dell'ammasso maggiormente predisposte ai fenomeni di instabilità, evidenziando le zone critiche prioritarie per il monitoraggio alla scala del versante. A tal fine, l'analisi specifica condotta sulle zone in contropendenza o a strapiombo, identificate analiticamente attraverso valori negativi del vettore normale alla superficie Nz ($Nz < 0$), si rivela un approccio utile per l'individuazione delle aree critiche. Lo studio ha, inoltre, prodotto risultati in termini di quantificazione volumetrica dei blocchi potenzialmente instabili, che forniscono input numerici essenziali per la progettazione ingegneristica delle opere di mitigazione. L'analisi condotta sulla distribuzione dei volumi dei blocchi potenzialmente instabili ha rivelato uno scenario caratterizzato da magnitudo significative; analizzando nel dettaglio i percentili della distribuzione, si osserva che la Mediana (p50) si attesta su un valore di 14 $m^3$, un dato che indica inequivocabilmente come la metà delle potenziali instabilità identificate coinvolga già masse rocciose di dimensioni considerevoli. Proseguendo nell'analisi della curva di distribuzione, il 75esimo percentile (p75) si stabilizza su un volume di 28 $m^3$, delineando così il limite superiore per la maggioranza della popolazione di blocchi analizzati. Dall'osservazione della coda superiore della distribuzione, rappresentata dai valori p90 e p95, emergono gli scenari più critici: la distribuzione mostra infatti una coda significativa verso valori molto più elevati, con il 90esimo percentile che raggiunge gli 86 $m^3$ e il 95esimo percentile che raggiunge l'impressionante volume di 150 $m^3$.

Il modello digitale tridimensionale elaborato non sembra costituire, quindi, solo una rappresentazione geometrica statica, ma si configura come un utile strumento diagnostico dinamico, capace di supportare in modo continuativo il monitoraggio e l'analisi dell'evoluzione della parete rocciosa nel tempo, offrendo così un supporto decisionale indispensabile per la mitigazione del rischio all'interno di un'area altamente vulnerabile e di non facile accesso attraverso le pratiche tradizionali. Guardando agli sviluppi futuri di questa linea di ricerca, l'attenzione si focalizzerà strategicamente sull'acquisizione di parametri geomeccanici sito-specifici, necessari per affinare le valutazioni di stabilità del versante passando da un approccio geometrico a uno più rigoroso dal punto di vista geomeccanico. Inoltre, i volumi dei blocchi identificati in questa fase saranno dati di input fondamentali per le future analisi tridimensionali di propagazione dei blocchi, permettendo così di definire con precisione le traiettorie di caduta all'interno dell'area e gli scenari di rischio per i numerosi elementi esposti nell'area urbana di interesse.

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## ABSTRACT

Rockfall phenomena influence human activities in areas where anthropic expansion reaches the slopes of the reliefs. The rockfall hazard assessment is particularly required when exposed elements exist in the area, causing the conditions for a risk scenario. Since direct data acquisition (*i.e.*, in contact with the rock face) for rockfall hazard characterization is not always feasible due to logistical constraints and exposure to the factors generating the hazard, indirect (*i.e.*, remote) approaches have emerged over the past decades as a reliable solution. The main goal of these approaches is to generate a three-dimensional model of the analyzed rock mass, making it possible to extract parameters for the characterization of discontinuity systems and to perform stability analyses remotely.

The proposed case study focuses on a portion of the eastern sector of Mount Pellegrino (Sicily), overlooking an urban area of Palermo that includes, among other elements, the monumental cemetery of Santa Maria dei Rotoli. The mount, a carbonate massif that rises 606 a.s.l. within the city of Palermo, has historically been affected by rockfall phenomena. The cemetery represents a vulnerable element to be preserved, both as an artistic and historical heritage site and as a place where human lives are exposed due to tourism and religious activities. In this context, a Terrestrial Laser Scanning (TLS) survey was conducted, allowing the acquisition of a high-resolution 3D point cloud model of the rock face. Once processed and filtered, the point cloud can be considered the geometric basis of a digital twin of the investigated rock front, serving as the raw dataset from which to extract useful information for the geomechanical characterization. Whitin this context, the application of rock mass classification systems can be considered a first digital twin–enabled step, allowing the identification of more critical sectors where specific analyses were subsequently performed to determine quantitative parameters for hazard analysis.


***Keywords***: *digital twin, remote sensing, TLS, rockfall, rock mass characterization*

## INTRODUCTION

Among gravitational phenomena, rockfalls are some of the most rapid and unpredictable in terms of triggering mechanisms (Hungr *et alii*, 2014; Varnes, 1978). This phenomenon represents a major threat to human activities, particularly in areas where anthropogenic expansion has encroached upon mountain slopes. Consequently, rockfall hazard assessment is a fundamental requirement when exposed elements such as people, infrastructure, and cultural heritage are present, posing significant risks scenario.

The direct approach, based on guidelines issued by the International Society for Rock Mechanics (ISRM 1978), involves acquiring geometric parameters (orientation, spacing, aperture, persistence, roughness) and mechanical properties (uniaxial compressive strength) to characterize discontinuities by using instrumentation (geological compass, metric tape, profilometer, sclerometer) in direct contact with the rock face. However, logistical constraints such as the inaccessibility of vertical cliffs and the exposure of surveyors to hazardous conditions often render traditional methodologies impractical.

Consequently, in recent decades, indirect methodologies (remote sensing) have emerged as reliable solutions to overcome these limitations. The primary objective of these approaches is the generation of a three-dimensional model of the analyzed rock mass using photogrammetric (Cappadonia *et alii*, 2023; Gallo *et alii*, 2021; Jordá Bordehore *et alii*, 2017; Menegoni *et alii*, 2018), LiDAR (Abellán *et alii*, 2014; Jaboyedoff *et alii*, 2012; Oppikofer *et alii*, 2009), and thermal (Grechi *et alii*, 2021; Mineo S. *et alii*, 2022; Mineo S. *et alii*, 2025) processing. This model, or "Digital Twin," allows for the extraction of parameters necessary for characterizing discontinuity systems (Dewez *et alii*, 2016; Gigli & Casagli, 2011; Riquelme *et alii*, 2014), assessing the expected magnitude (Caliò *et alii*, 2023; Chen *et alii*, 2017; Mineo G. *et alii*, 2025), and performing remote stability analyses (Gigli *et alii*, 2022), thus ensuring operator safety and high data precision.

Mount Pellegrino, a carbonate massif rising to 606 m a.s.l. within the city of Palermo, has historically been affected by slope instability phenomena. In particular, a portion of the eastern slope overlooks the monumental cemetery of Santa Maria dei Rotoli. This area represents a critical element of vulnerability, both as a historical-artistic heritage site to be preserved and as a location frequented daily by visitors and workers, thereby exposing human lives to direct risk.

In the past, the Mount Pellegrino area was extensively studied using direct approaches (Cafiso & Cappadonia, 2019; Cappadonia *et alii*, 2021), while remote sensing approaches have only recently been implemented for certain sectors ( Mineo G. *et alii*, 2025; Mineo G. *et alii*, 2024).

This study illustrates the application of such techniques to the Rotoli slope, where the Santa Maria dei Rotoli Cemetery is located, an important historical-artistic site in the city. The chosen acquisition methodology is based on Light Detection And Ranging (LiDAR) technology implemented via Terrestrial Laser Scanning (TLS), which allowed for the acquisition of a high-resolution point cloud of the investigated rock slope.

## STUDY AREA

The study area encompasses a specific sector of eastern Mount Pellegrino (Sicily, Southern Italy), a location of strategic importance for the city due to its naturalistic, cultural, and religious value. The investigated rock slope directly overlooks the Santa Maria dei Rotoli monumental cemetery (Fig. 1).

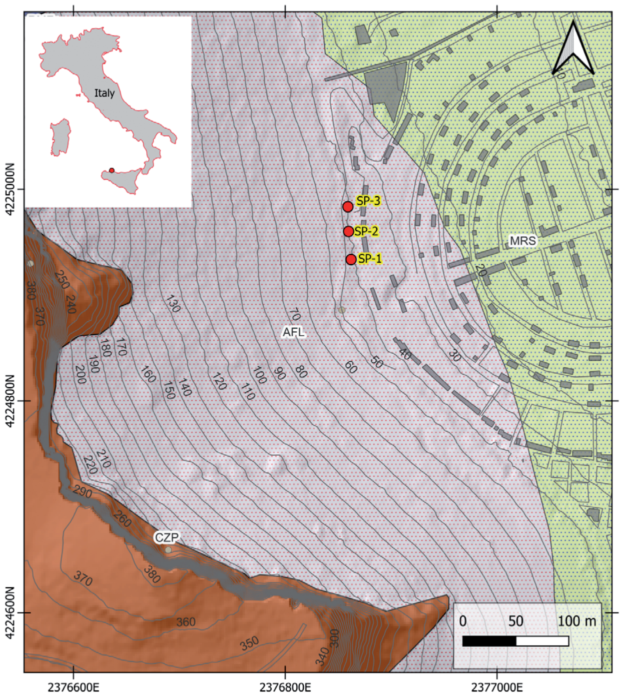



*Fig. 1 - Geological setting of the eastern side of Mount Pellegrino overlooking to the cemetery: Scree cones, detritus and poor sorted materials of variable thickness (AFL - Upper Pleistocene-Holocene); Calcarenites, calcirudites, and sands (MRS - Calabrian); modified from Servizio Geologico D'Italia, 2023; photographic shot of the study area; SP1-2-3 Scan Survey Station Position*

The complex geological setting of the area results from the overthrust of carbonate platform terrains, subsequently dissected by Plio-Quaternary extensional and transtensional tectonic events characterized by high-angle normal faults (Catalano *et alii*, 2013). These events produced the current morphological setting, which consists of an isolated carbonate relief separated by depressions filled with marine deposits.

The geological units making up the rock mass originate from the deformation of the Panormide Carbonate Platform. Specifically, these consist of Upper Cretaceous reef limestones (Cozzo di Lupo Formation, CZP). Lithologically, these are massive or coarsely bedded limestones, varying in color from white to light gray, and are often rich in Rudist fossil remains. The geological evolution of the area has thus established a morphological framework predisposed to instability; in this urban context, such conditions imply a high risk of slope failure for this sector of Palermo City.

## METHOD

For the remote characterization of the rock face, a methodology based on Terrestrial Laser Scanning (TLS) data acquisition and 3D point cloud processing was adopted an approach widely applied in recent decades (Abellan *et alii*, 2016; Gigli & Casagli, 2011). Furthermore, the choice of this methodology was required by both the strict regulations of the nature reserve where the site is located and the severe flight restrictions enforced over the Palermo area, which precluded alternative survey methods.

The survey campaign was carried out using a Terrestrial Laser Scanner (TLS), specifically the Riegl VZ-2000i model, which employs LiDAR technology (Fig. 2). This instrument allowed for safer acquisitions of the rock slope, by acquiring the spatial coordinates (x, y, z) and intensity of millions of points on the rock slope with high resolution. High positional accuracy was ensured by an e-Survey E-300 GNSS receiver

*Fig. 2 - Survey Station SP1 (left); overview of the cemetery and the rock slope above (right)*

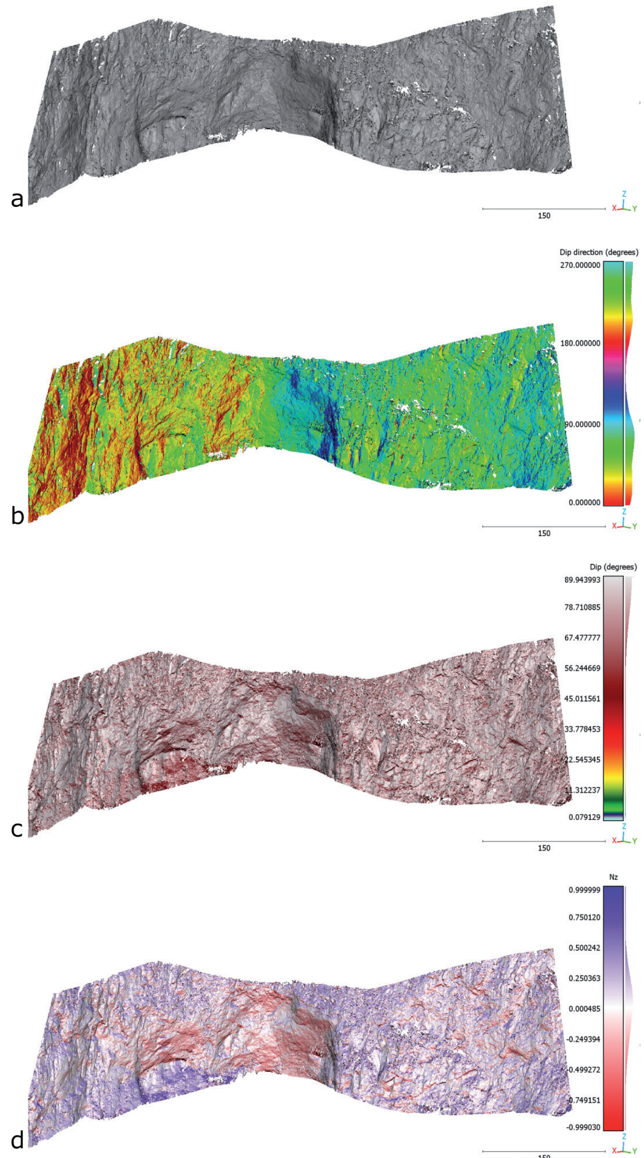



*Fig. 3 - 3D point cloud visualizations of the rock slope. (a) Raw point cloud displaying the slope morphology. (b) Point cloud classified according to Dip Direction (degrees). (c) Point cloud classified according to Dip angle (°). (d) Point cloud classified according to the vertical component of the normal vector (Nz)*

operating in Real-Time Kinematic (RTK) mode.

The presence of anthropogenic structures limited scan positions, as shown in Fig. 1, restricting the survey to a single sector (Fig. 2) from which three scans were conducted. The acquisition parameterization, defined based on the scanning distance and the expected reflectance of the investigated object, resulted in an acquisition time of approximately 1.5 hours.

The acquired raw scans were imported and processed using the RiSCAN PRO software. The processing phase included: *i*) alignment and registration in order to merge the different scans into a single global reference system; *ii*) removal of vegetation and non-relevant elements (noise) to obtain a filtered point cloud accurately representing only the rock surface. The resulting point cloud constitutes the digital twin of the studied rock slope, serving as the raw dataset for subsequent geomechanical analyses.

Normal vector estimation was performed within the CloudCompare environment using a local plane fitting approach. The algorithm computes the unit normal vector for each point by fitting a plane to its nearest neighbors via the Least Squares method. This process enables the derivation of the local orientation of the rock surface, which is fundamental for the subsequent extraction of orientation-derived information.

This model served as the basis for extracting quantitative data essential for hazard assessment, presented here through a series of graphical elaborations (Fig. 3). Initially, the dataset was visualized in RGB (True Color/Grayscale) to facilitate a detailed visual inspection of the slope (Fig. 3a). Subsequently, structural features were characterized by classifying the point cloud according to geometric parameters: Dip Direction (Fig. 3b) and Dip Angle (Fig. 3c), which highlight the orientation and inclination of the rock planes. Finally, the vertical component (Nz) of the normal vector previously calculated was extracted following the methodology proposed by (Matasci *et alii*, 2018) (Fig. 3d). Given the lithological uniformity of the entire face, the rock mass was partitioned into distinct structural domains based on exposure (face orientation). This subdivision was necessary to mitigate orientation bias during the extraction of discontinuity sets; by analyzing areas with similar dip directions and dip angles separately, we ensured that sets sub-parallel to the local face orientation were not statistically underrepresented. These homogeneous zones were used to define the main discontinuity.

| ***Zone*** | **Slope (Dip dir/dip)** | **J1** | **J2** | **J3** | **J4** |
|---|---|---|---|---|---|
| ***Zn 1*** | 013/87 | 143/85 | 241/80 | 148/35 | - |
| ***Zn 2*** | 220/72 | 201/89 | 267/66 | 131/22 | 352/05 |
| ***Zn 3*** | 066/82 | 245/62 | 116/86 | 189/73 | - |

*Tab. 1. - Summary of mean orientation parameters for the analyzed zones. The table lists the mean attitude of the slope and the main discontinuity sets (J1-J4) identified via DSE for each zone (Zn 1, Zn 2, Zn 3). Angular values are reported in degrees as Dip Direction/Dip Angle*

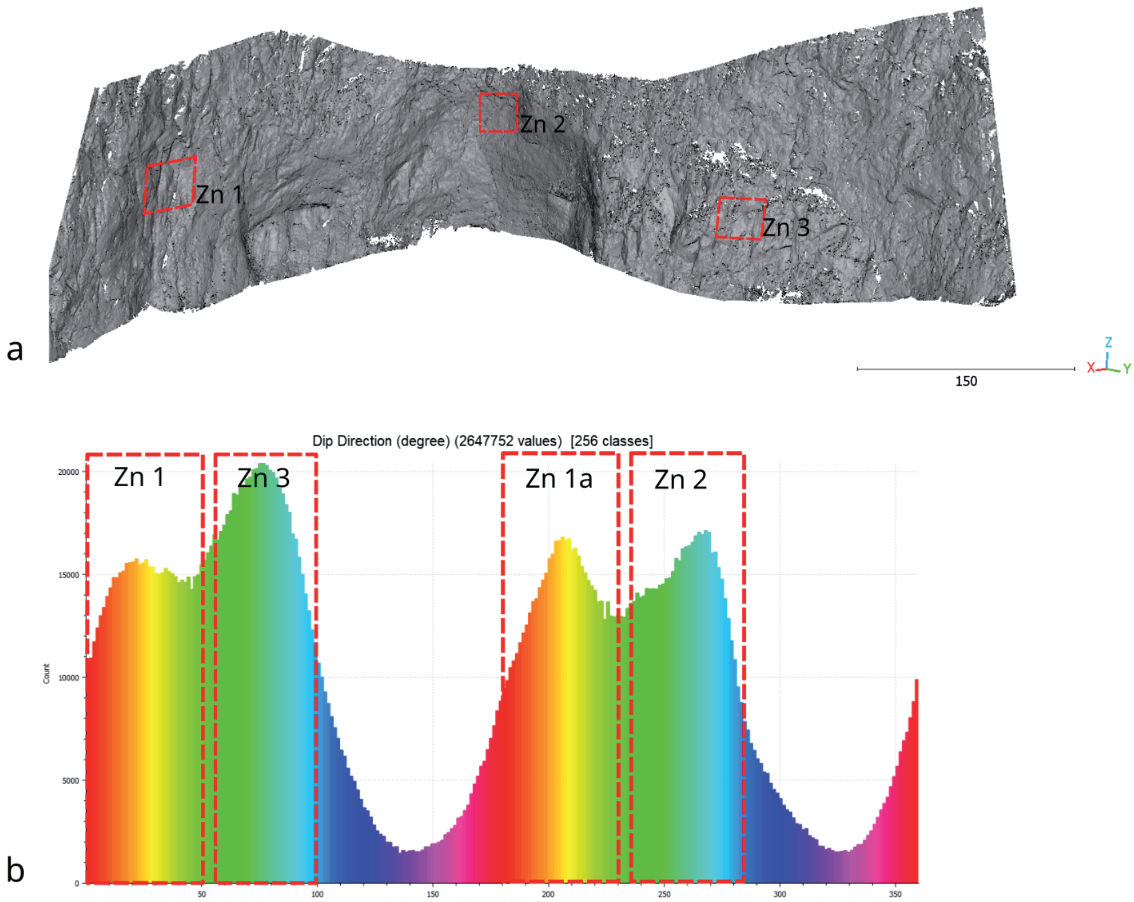



*Fig. 4 - Dip Direction analysis and definition of Scan Windows. (a) 3D point cloud of the investigated rock slope. Red dashed rectangles indicate the spatial location of the selected scan windows within the structural zones Zn 1, Zn 2, and Zn 3 identified in the histogram. (b) Histogram showing the frequency distribution of Dip Direction values (°). The colored bars indicate the number of points for each direction. Four zones (Zn 1, Zn 3, Zn 1a, Zn 2) corresponding to frequency peaks are highlighted with red dashed rectangles*

## RESULTS

Data alignment and filtering were carried out using RISCAN PRO software, yielding a comprehensive point cloud comprising approximately 300 million points.

Based on exposure (Orientation/Aspect) and slope geometry, the overall point cloud was classified and segmented into structurally homogeneous zones (Zn, fig. 4). In particular, the following 4 main patterns were identified:

- Zn 1: Characterized by an average exposure towards the East-North East with a high dip angle (Slope: 013/87).
- Zn 2: Average exposure towards the East-South East, characterized by sub-vertical attitude but with overhanging portions (Slope: 220/72).
- Zn 3: Average exposure towards the East-North East with a high dip angle (Slope: 066/82).
- Zn 1a: A specific pattern located within Zn.

Representative scan windows, each approximately 30 × 30 m in size, were selected within each defined homogeneous zone for the detailed characterization of primary discontinuity sets.

Structural analysis was conducted using the Discontinuity Set Extractor (DSE) software (Riquelme *et alii*, 2014), employing a semi-automatic extraction workflow applied to each selected window (Fig. 5). The configuration of the processing parameters followed the standard values proposed by the authors (Riquelme *et alii*, 2014). Specifically, the local curvature calculation and normal vector estimation were performed using a k-Nearest Neighbor (k-NN) value of 30 and a coplanarity tolerance of 0.2. The identification of the principal discontinuity sets was carried out via Kernel Density Estimation (KDE), setting the bin size to 6 and the minimum angle between principal poles to 30°.

Finally, the assignment of points to each Discontinuity Set (DS) was defined by a cone angle of 30°, while the spatial cluster analysis, aimed at isolating individual fracture planes, adopted a statistical threshold of 2 sigmas. This rigorous

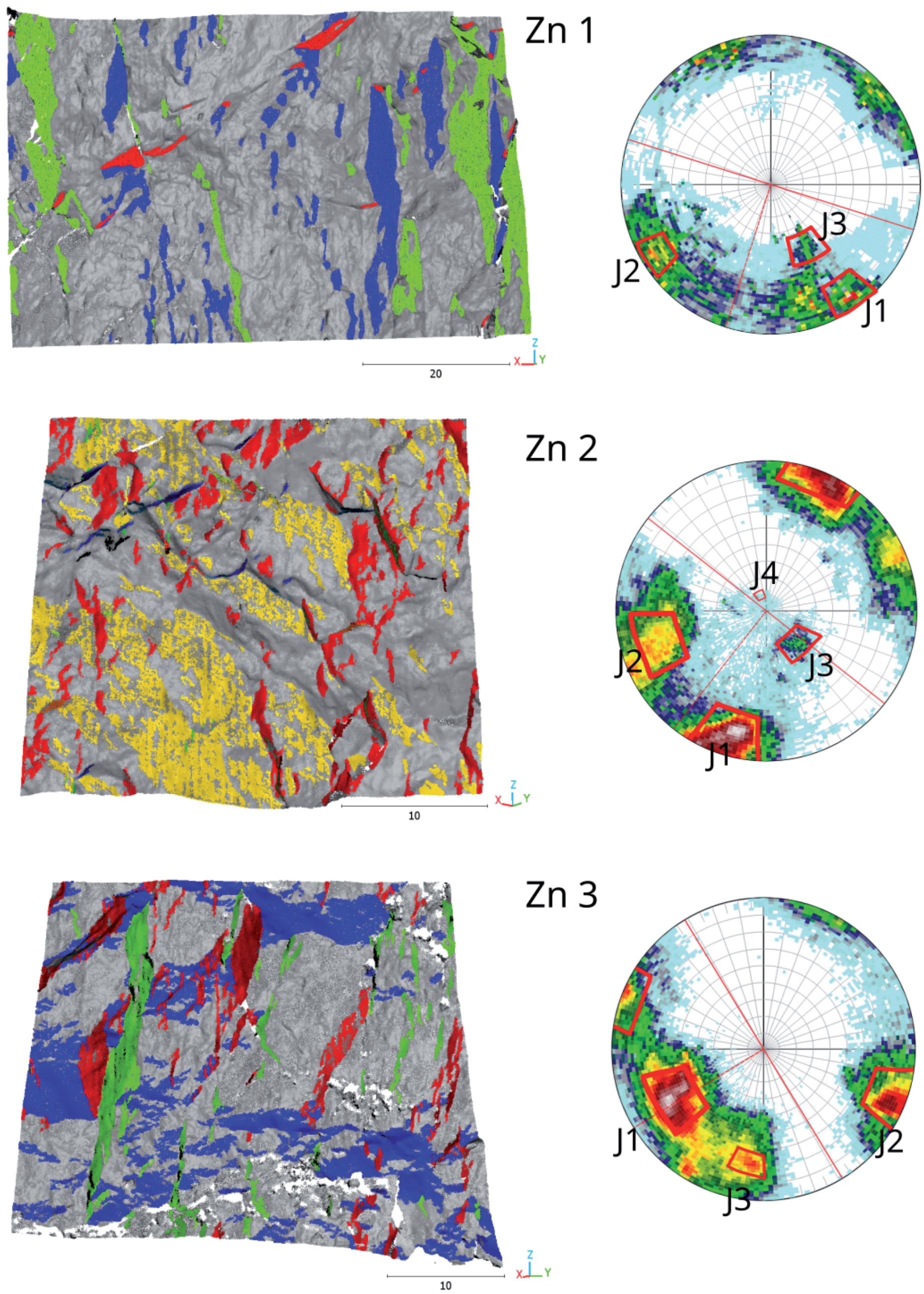
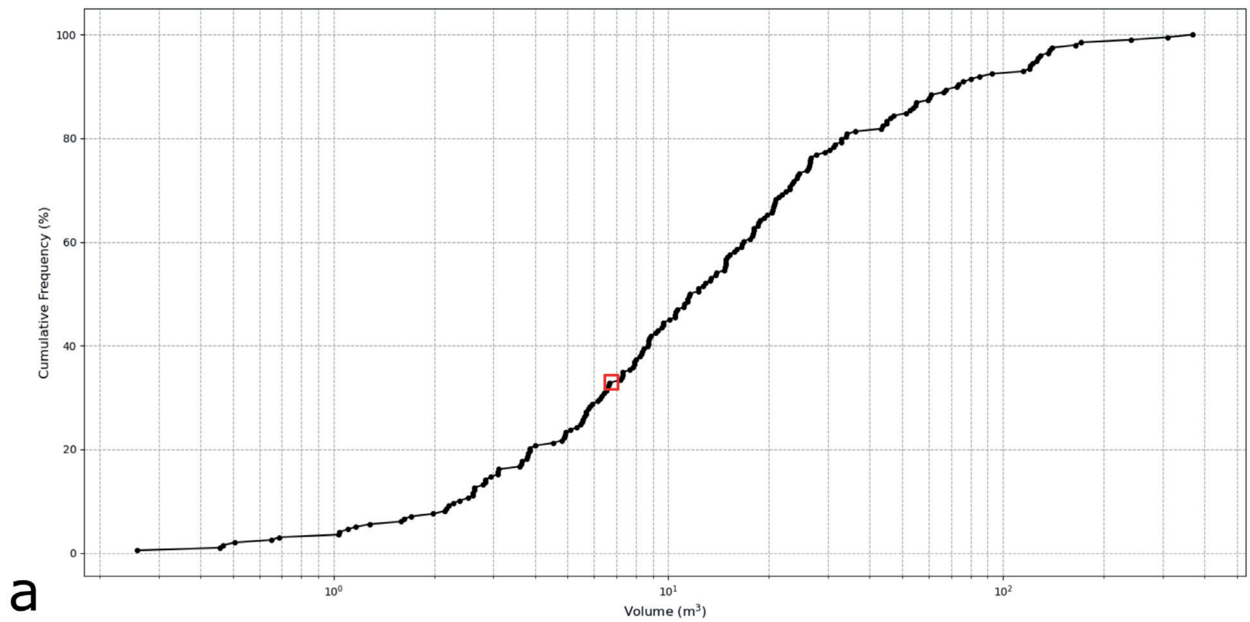
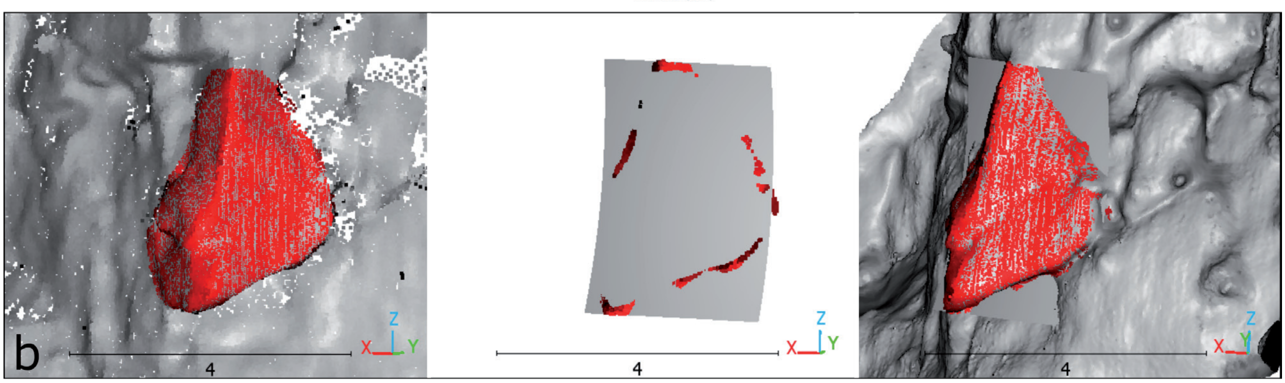



*Fig. 5 - Results of the semi-automatic discontinuity extraction for the analyzed zones (Zn 1, Zn 2, Zn 3). For each zone: (left) The classified 3D point cloud, where different colors (red, green, blue, yellow) indicate points assigned to the identified Discontinuity Sets on the rock surface. (right) The corresponding stereographic projection (pole density), where high-concentration areas represent the mean orientation of the planes. Red polygons highlight the principal clusters identified by the algorithm, labeled J1, J2, J3 (and J4 for Zn 2)*

parameterization allowed for the precise definition of the main discontinuity sets (J) summarized in Table 1.

The presence of overhanging sectors represents a critical factor for rock slopes stability assessment. To address this, the vertical component of the normal vector (Nz) was computed for each point. As illustrated in Figure 3d, negative values (Nz < 0) identify overhanging (downward-facing) surfaces, whereas positive values correspond to upward-facing orientations. This geometric criterion guided the recognition and segmentation of 198 potentially unstable rock blocks. Subsequently, following the methodology proposed by Mineo G. *et alii* (2025), a volumetric estimation of the isolated blocks was performed using the "Compute 2.5D Volume"

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algorithm. Figure 6 displays the distribution of the calculated volumes for the identified critical blocks.

## DISCUSSION AND CONCLUSIONS

The application of a "Digital Twin" based framework to the Mount Pellegrino slope overlooking the urban cliff of Palermo where the Rotoli cemetery is located demonstrated the effectiveness of remote sensing techniques in assessing parameters useful for rockfall hazard characterization in complex settings.

TLS data acquisition successfully overcame the limitations of direct access, providing a dense and accurate dataset. The segmentation into homogeneous zones (Zn 1, Zn 2, Zn 3) and the use of algorithms such as those implemented in DSE enabled the rapid and efficient extraction of discontinuity system orientations. Regarding the definition of homogeneous zones, subset Zn 1a was identified as a structural feature in Zn 1 controlled primarily by the presence of the J1 discontinuity set, demonstrating the utility of the approach for both the identification of main homogeneous zones and their further detailed characterization.

Zn 2 rock slope is mainly characterized by an overhanging dip. Although a deterministic definition of the failure mode would require further specific stability analyses, the geometric arrangement suggests that this area is the most susceptible to instability.

Although the automated analysis identified distinct clusters for each zone (Fig. 5), a transversal analysis between the various homogeneous areas allows the discontinuities to be grouped into three main systems, moving beyond the site-specific nomenclature assigned by the algorithms:

1. Set A (Bedding), characterized by low-to-medium dip angles (20-35°) towards SE, corresponding to sets Zn1-J3 and Zn2-J3.
2. Set B (Main tectonic), characterized by high angles (>60°) dipping SW, clearly recognizable in the overlap between Zn1-J2 and Zn3-J1.
3. Set C (Conjugate system), sub-vertical with dip directions varying between SE and S, grouping families Zn1-J1 and Zn3-J3.

Local orientation variations (*e.g.*, Zn2-J1) highlight the structural complexity of the fractured rock mass and the necessity for zonal segmentation. Conversely, the absence of set A in Zn3 could be due to the tight aperture of the discontinuity system, resulting in its non-detection by the algorithms for that zone. This limitation, widely acknowledged in the relevant literature (Riquelme *et alii*, 2014; Sturzenegger & Stead, 2009), can be overcome, where possible, by integrating direct acquisitions (Jordá Bordehore *et alii*, 2017; Mineo G. *et alii*, 2024) or through the integration of discontinuity trace recognition algorithms (Mehrishal *et alii*, 2025; Umili *et alii*, 2013).

The specific analysis of overhanging zones (Nz < 0) proved crucial for identifying potentially unstable rock mass portions.

Finally, volume quantification (Fig. 6) provides essential numerical input for the design of mitigation works. In particular, the statistics of the potentially unstable block volumes reveals a distribution characterized by significant magnitudes. Specifically:

- Median (p50): The median value is observed at 14 m³, indicating that half of the identified potential instabilities already involve considerable rock masses.
- 75th Percentile (p75): This value settles at 28 m³, delineating the upper limit for the majority of the population.
- Upper Tail (p90 and p95): The distribution exhibits a significant tail towards larger values, with the 90th percentile at 86 m³ and the 95th percentile reaching 150 m³.

These percentiles highlight a critical scenario: the potential hazard is not limited to minor fragmentation or small blocks fall but also involves the potential detachment of large and potentially unstable rock blocks with volumes of several tens of cubic meters.

In conclusion, the three-dimensional digital model constitutes not merely a geometric representation, but a genuine diagnostic tool that allows for monitoring and analysis of the rock slope evolution over time, supporting decision-making for risk mitigation within the monumental cemetery area. Future developments of this research will focus on the acquisition of site-specific geomechanical parameters to refine slope stability assessments. Furthermore, the identified block volumes will serve as crucial input for 3D rockfall propagation analysis, allowing to precisely mapping the risk scenarios within the area.

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