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AERIAL PHOTOGRAMMETRY USED AS A QUICK PROCEDURE FOR ROCK MASS STABILITY ANALYSIS IN A NATURE RESERVE

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EXTENDED ABSTRACT

La caratterizzazione geostrutturale per la valutazione della stabilità di ammassi rocciosi situati in aree protette rappresenta una sfida tecnica legata principalmente alle restrizioni che gravano sul territorio e che impediscono l'esecuzione di rilievi invasivi. Se a questo si aggiunge la cattiva accessibilità per rilievi convenzionali, lo studio di un ammasso roccioso diventa un'attività a rischio per gli operatori specializzati che effettuano misure sul campo, con conseguenti costi elevati di gestione e tempi di esecuzione relativamente lunghi. Il progresso tecnologico e il crescente utilizzo di aeromobili a pilotaggio remoto hanno permesso di ottenere con successo soluzioni alternative ai rilievi tradizionali mantenendo fedele il dato acquisito.

Questo lavoro mira a evidenziare i vantaggi nell'adottare un approccio speditivo che integra la tecnica fotogrammetrica allo studio di un ammasso roccioso, al fine di superare i limiti delle misure classiche di campagna in questo caso nell'ambito di delicate strategie di gestione delle riserve naturali. Numerose riserve in tutto il mondo sono infatti minacciate dall'instabilità dei versanti rocciosi, considerata tra le principali cause di rischio. L'area di studio scelta per questo lavoro è la Riserva Naturale Orientata dei Laghetti di Marinello (Sicilia nord-orientale), che offre numerosi percorsi turistici pedonali verso cinque laghi salmastri sub-paralleli all'imponente ed instabile falesia che si estende per circa 2 km di lunghezza. Gran parte del promontorio ha subito in passato numerosi eventi franosi, tra cui un'imponente frana avvenuta in tempi storici che interessò duramente l'antica acropoli Tyndaris. Tuttavia, la gestione dei rischi naturali all'interno di determinati contesti è precaria e molto spesso assente, esponendo, talvolta inconsapevolmente, i turisti a svariati pericoli. L'obiettivo principale del presente studio è dunque quello di analizzare la stabilità del promontorio sulla base delle informazioni tecniche ricavate dall'elaborazione digitale del modello dell'ammasso roccioso costruito mediante fotogrammetria aerea. Questa tecnica sfrutta i potenti algoritmi della Structure from Motion (SfM) per ricavare un modello tridimensionale correttamente georiferito e metricamente scalato del versante.

Successivamente, attraverso una suddivisione dell'ammasso in tre differenti settori chiave, sono stati applicati approcci semi-automatici per l'estrazione di dati spaziali di discontinuità, validati preliminarmente su stazioni di misura accessibili sul campo e successivamente estesi a un'area della riserva significativamente più vasta. Questo approccio metodologico ha consentito di localizzare i principali elementi strutturali e le aree di provenienza di possibili distacchi gravitativi da parte di blocchi di roccia in equilibrio precario. I dati spaziali ricavati digitalmente sono stati utilizzati per effettuare un'analisi cinematica dell'ammasso roccioso, evidenziando tre differenti modelli di rottura instabili quali: scivolamento planare, con una percentuale media di poli critici rispetto a quelli totali del 13.35 % nei tre diversi settori; scivolamento di cuneo con una percentuale media di poli critici del 29.36 %, che denota una propensione maggiore a questo tipo di cinematismo; ribaltamento flessurale con una percentuale media del 25.30 % di poli critici. Sulla base dei modelli di rottura è stata eseguita un'analisi di stabilità numerica mediante il calcolo del fattore di sicurezza con il metodo all'equilibrio limite, sia in condizioni statiche che pseudostatiche, con risultati spesso inferiori a 1 per tutti i cinematismi presi in considerazione. L'analisi è stata ripetuta anche in termini probabilistici, per la stima della probabilità di accadimento lungo ciascuna discontinuità critica. Infine si è effettuata una stima volumetrica dei blocchi ritenuti in condizione di equilibrio precario pervenendo ad una conoscenza dettagliata delle problematiche legate all'instabilità del promontorio della riserva. L'approccio proposto è pertanto un utile strumento di gestione e valutazione speditiva di aree a maggiore rischio crolli, per garantire la gestione sicura e la fruizione sostenibile dei siti, ma anche per il corretto impiego delle risorse economiche destinate alle successive misure di mitigazione.

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ABSTRACT

The geostructural characterization of rock clusters, located in poorly accessible areas of nature reserves, represents a challenge for the specialized technicians who carry out field rock mass measurements. This paper aims to highlight the advantages in adopting a quick approach that introduces the photogrammetric technique to overcome the limitations of conventional field measurements. In this study, the aerial photogrammetry, combined with the powerful algorithms of the Structure from Motion technique, allowed generating a detailed rock mass model of a sub-vertical cliff affected by instability features threatening the safe fruition of a nature reserve. Quantitative and qualitative data on the spatial orientation of discontinuities and on location of major structural elements were achieved. The digitally derived spatial data were used to perform a kinematic analysis of the rock mass, highlighting the most recurrent unstable failure patterns, for which the stability and the probability of failure were numerically calculated in both static and dynamic conditions.

***Keywords**: airborne photogrammetry, rock mass, nature reserve, characterization of rock slopes*

INTRODUCTION

Numerous places of outstanding natural beauty are protected around the world because of their importance for flora and fauna or because of features of geological interest. Such areas are generally protected by reserved management aimed at conservation and providing special opportunities for study or research. This makes nature reserves common attractions, especially when recognized among tourist trails or resorts, that require safe use and risk management plans. Indeed, there are a number of natural hazards that can be counted among the potential threats to both the conservation of the environment and the enjoyment of the reserve. Fire risk, for example, is extremely high in places affected by hot weather or abnormal heat waves (JOHANSSON, 2021) while hurricanes, sea level rise, and tsunamis pose natural hazards in coastal ecosystems (Dudley *et alii*, 2015). In relation to geological aspects, gravity phenomena substantially threaten nature reserves, cultural heritage, archaeological sites, and geosites, (e.g., Calcaterra *et alii*, 2014; Pappalardo *et alii*, 2018, 2021; Tronti *et alii*, 2021). This study focuses on the impact of rockfalls affecting the tourist accessibility of the Marinello Lakes Nature Reserve, located in northeaster Sicily (Italy) at the foot of the 250 m high Cape Tindari rock cliff. Over the past few years, the peculiarity of the geological and geomorphological structure of the Cape Tindari promontory has led to the occurrence of numerous rockfall phenomena, which are still active and have forced the partial disruption of those pedestrian paths running in the close proximity of the foot of the rock wall. The cliff is affected by a poor accessibility for conventional rock mass surveys due to its sub-vertical morphology and the presence of vegetations. In such a setting, remote sensing techniques based on aerial sensors (Giordan *et alii*, 2018), allow extensive surveying of a relatively large and unstable area, acquiring information homogeneously over the entire area investigated, even with millimeteric-centimetric resolutions (Sturzenegger & Stead, 2009; Brideau *et alii*, 2011; Francioni *et alii*, 2018; Mineo *et alii*, 2021). Their usefulness mainly relies on the possibility of surveying large areas in short times and safety. Photogrammetry, therefore, allows the reconstruction of digital outcrops, providing 2D or 3D spatial information from features and elements visible in two or more images acquired from different viewpoints (Westoby *et alii*, 2012). This approach was undertaken for the rock mass survey in the studied reserve, with the aim of collecting data useful for the stability assessment along the main discontinuity sets in a sector of the nature reserve. Starting from a survey by Unmanned Aerial Vehicle (UAV), a detailed 3D model of the cliff was achieved, and discontinuity data were extracted from the model. This procedure ensures a high datum reliability and proved a valid remote surveying tool in the literature experience (Casagli *et alii*, 2017;Salvini *et alii*, 2018; Rossi *et alii*, 2018; Mineo *et alii*, 2022). With respect to the case study presented herein, the semiautomatically extracted spatial data were statistically analysed on stereograms, and a kinematic analysis was carried out by taking into account the main failure patterns. Resulting data were used to perform a stability analysis according to both a deterministic and probabilistic approaches for the estimation of the factors of safety, under static and dynamic conditions, and the probability of failure.

THE STUDY AREA

The Marinello Lakes Nature Reserve is located along the Tyrrhenian ridge of the Peloritani Mountains (Fig. 1), which geologically represent the extreme southern edge of the Calabria-Peloritani Orogen (Fig. 1a). It represents a segment of the Apennine-Maghrebid Orogene, consisting of a "multilayer" edifice composed of several overlying thrust systems (Atzori & Vezzani, 1974) with metamorphic rocks of Paleozoic age. This area is located in the northeastern part of Sicily, in the middle of the Gulf of Patti. From a geomorphological point of view, the promontory has a NW-SE trend, in accordance with the main tectonic lines, with a total extension of about 2200 m and the rock walls reach a height of about 300 meters above sea level. This strategic location has made, historically, the study area a key spot from both military and commercial points of view. Early XIX century historical sources report also the existence of a natural harbour, described as an ancient sand deposit from marine currents and wind (Crisà *et alii*, 2015), probably located at the Oliveri Bay (Bottari *et alii*, 2009), in the close proximity of the reserve studied herein. Five brackish lakes and a complex system of littoral cordons constitute a natural environment of great scientific interest because of their rapid and continuous morphological evolution (Fig.1b). According to historical cartographies, the genesis of these brackish ponds likely dates back to the 19th century, when a complex system of littoral cordons developed more or less parallel to the shoreline and evolved, progressively delimiting a series of coastal lagoons and littoral arrows in continuous and rapid transformation (Privitera *et alii*, 2007). The area falls within a context of great landscape and naturalistic value and is characterized by unique geological, ecological, biological, faunal and vegetation peculiarities. The Tindari promontory and the Oliveri lagoons were declared a protected area in 1998 with the establishment by the Sicilian Region of the Marinello Lakes Nature Reserve. The Tindari promontory shows signs of a heavy tectonic history, and it is crossed by the "South Tyrrhenian System", which consists of an association of NW-SE trending faults and conjugate systems with NE-SW and N-S direction, developed in a trastensional regime. The faults identify a system consisting of a series of horsts (Capo Calavà, Capo Tindari, Tripi) in which Kabilo-Calabridi Units are exposed, alternating with graben (Patti, Oliveri-Falcone) in which powerful Middle-Supramiocene and Plio-Quaternary successions have accumulated (Lentini *et alii*, 2000). Therefore, the promontory is, therefore, intensely fractured and suffers from precarious slope stability conditions, thus posing a problem for the safe fruition of footpaths within the reserve (ISRM, 1978a).

METHODS

The considerable extension of the Tindari cliff, associated with its particular bad accessibility, strongly limits the conventional acquisition of rock mass data according to ISRM (1978) recommendations. The greatest difficulty is to survey the summit portions that are unreachable for field operations. There are only few available spots at the foot of the cliff where rock mass surveys can be carried out. Nevertheless, localized random measurements would be unrepresentative for a complete rock mass stability analysis, making the technical survey of the studied cliff a challenge. To overcome this limitation, and with the aim of achieving a detailed rock mass model for stability analysis purposes, an aerial photogrammetric survey was carried out by a DJI Mavic 2Pro, a four-propeller multi-rotor drone with a 20 Mpixel optical camera with a 1'' CMOS digital sensor and 28 mm lens focal length. The survey covered an area of 0.12 km^2 and an extremely detailed dense point cloud was achieved.

The image acquisition was carried out during three different flights for shots with 1) the optical axis of the camera tilted 0° from the horizontal to characterize the vertical rock walls, as well as areas with greater slope; 2) the optical axis of the camera tilted 45° from the horizontal for optimal definition of slopes with inclination between 35° and 50°; 3) the optical axis of the camera tilted 90° from the horizontal for nadiral shots. The flights were performed in manual mode because of the intricate geometry of

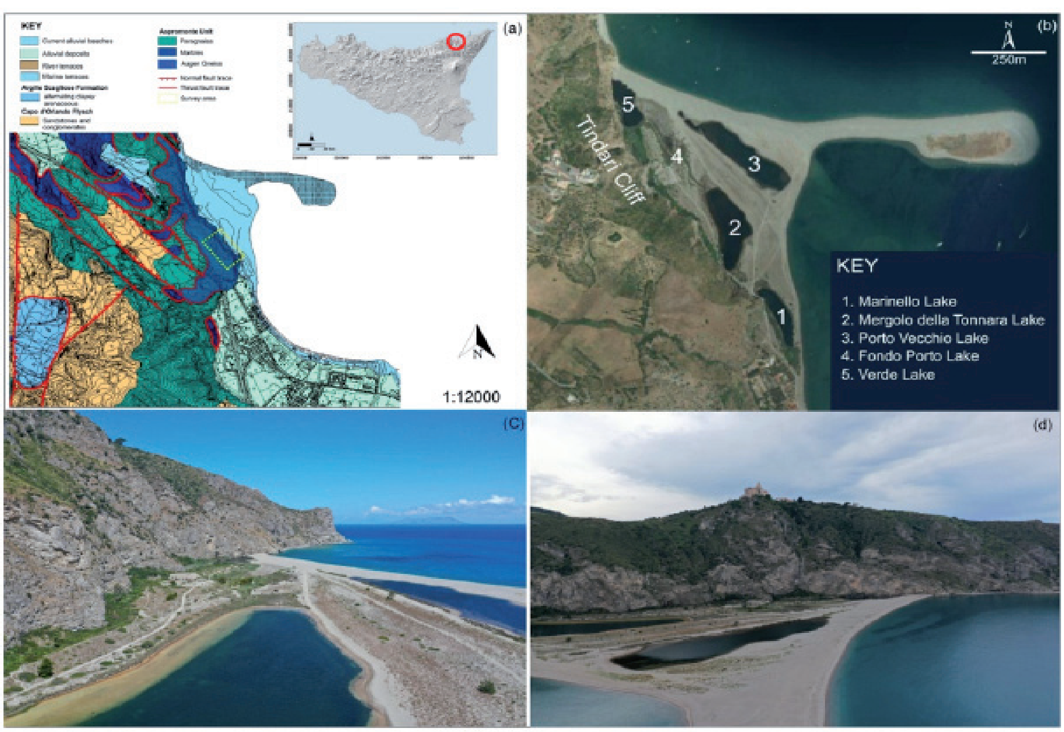

Fig. 1 - Geological map of the study area (Calìò et alii, 2023) (a); Satellite image highlighting the five lakes in the nature reserve (b); aerial photos of the study area (c), (d))

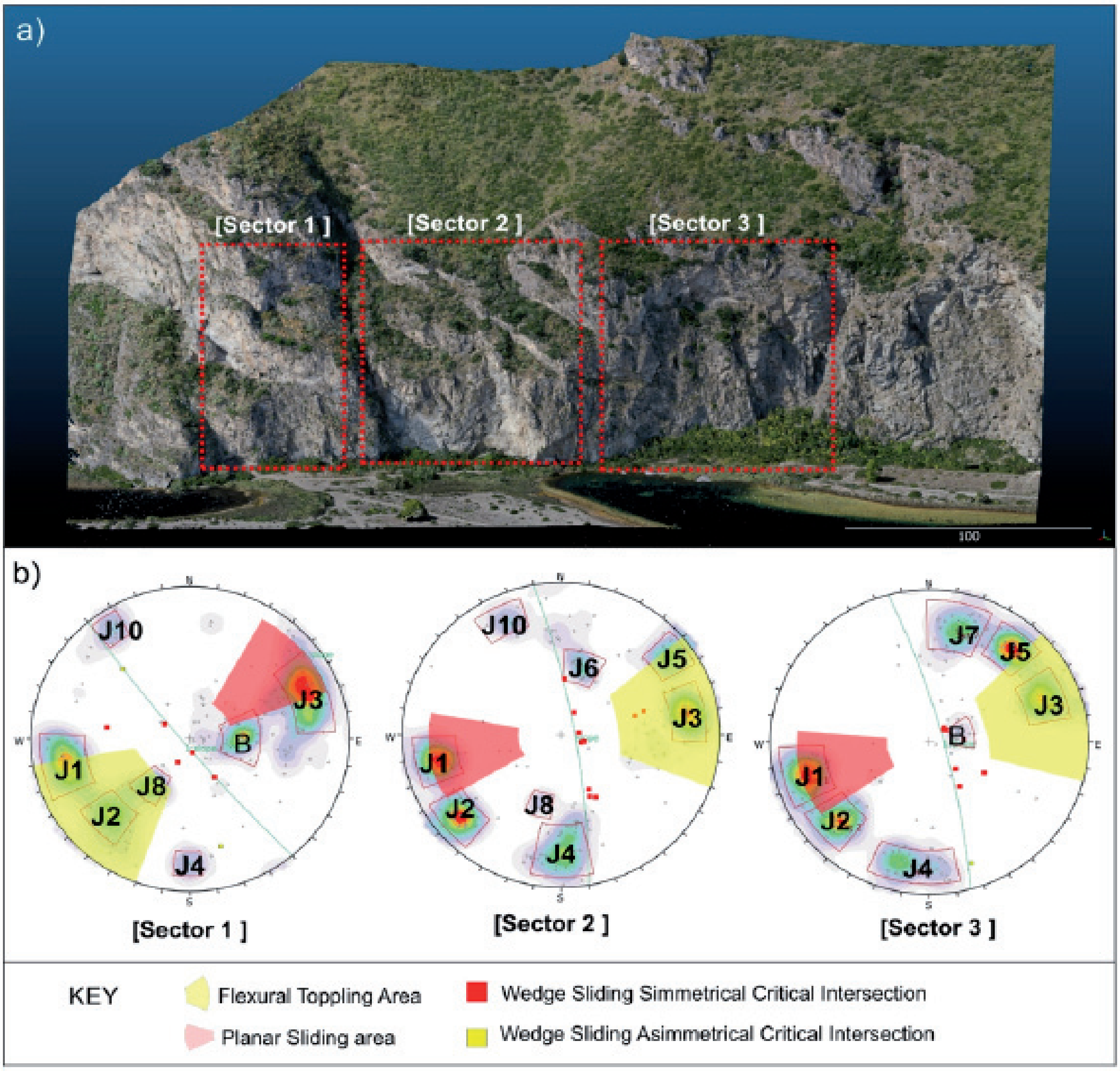

Fig. 2 - Summary of the UAV photogrammetric survey and resulting data: dense point cloud showing the survey sectors considered for discontinuity extraction (a); Geostructural data represented on stereograms belonging to each survey sector and related kinematic analysis (b).

the rock face; the drone was kept at a distance from the outcrop within a range that varied from 10 m to a maximum of 40 m, maintaining a nominal overlap and sidelap of at least 80 %and 70 %, respectively. In order to have a metrically correct and georeferenced datum of the final model, 20 high-visibility markers (GCPs) were placed homogeneously over the surveyed area for Network Real Time Kinematic (NRTk) position measurements through a Global Navigation Satellite Systems (GNSS). The photogrammetric processing was carried out by the Structure from Motion (SFM) technique, which is based on sophisticated image matching algorithms that use 2D images acquired from different viewpoints to reconstruct the three-dimensional geometry of an object or surface (Tonkin & Midgley, 2016).

A scattered point cloud of 139,524 million points was generated and further transformed into a dense cloud of 135 million points, with an accuracy of 1.9 cm/pixel. The good resolution, combined with the presence of the GCPs, returned a georeferenced rock cluster model to be exploited for geostructural and geomechanical purposes. Specifically, discontinuity extraction was carried out in 3 macro survey areas with sizes of 6,500 m^2 in sector 1 and 9,500 m^2 in sectors 2 and 3, located at key sectors of the rock mass, where the main instability features were suspected (Fig. 2a). The resulting point cloud was further processed by the open-source point cloud and mesh processing software CloudCompare, through a semi-automated survey exploiting the "scalar field" function for the extraction of the dip directions of the discontinuity planes. The data were then plotted on stereograms and statistically processed to group the main sets and to perform a kinematic analysis (Fig. 2b), to define those potentially unstable patterns that threaten the safe fruition of the reserve. Due to the complex degree of fracturing affecting the rock mass, the volumes of potentially detachable rock are numerous and highly variable in size. In order to estimate their average volume, a series of blocks were isolated (Fig. 3b) on the digital model of the rock mass through the "Compute 2.5D volume" tool implemented in the CloudCompare software, which allows the rasterization of these blocks associated with the creation of a discontinuity plane ideally unbounding each block along an unfavourable plane (Fig. 3c), thus calculating the volumetric difference between the reference plane and the block itself (Štroner, 2019), (Fig. 3b, c, d). This approach has also been used for estimating volume changes applied to morphological slope analysis (e.g Wheaton *et alii*, 2009). Finally, the stability of the slope was quantified through the limit equilibrium method and the factor of safety was calculated under static and dynamic conditions. Moreover, the probability of failure for the key failure patterns was calculated by considering a set of probabilistic parameters (joint spatial orientation and their standard deviation) and all the known field variables (slope parameters, physical mechanical properties of the rock and joints).

ROCK MASS DIGITAL SURVEY ON DENSE POINT CLOUD

In this work, the rock mass survey was carried out on the three-dimensional model, using the open-source software CloudCompare to extract the orientation data of discontinuities at three surveying windows. The used software exploits normals, defined as a vector quantity that determines the orientation of any geometric entity, such as a point or surface, associated with each individual point in the cloud. It is therefore possible to identify all points with

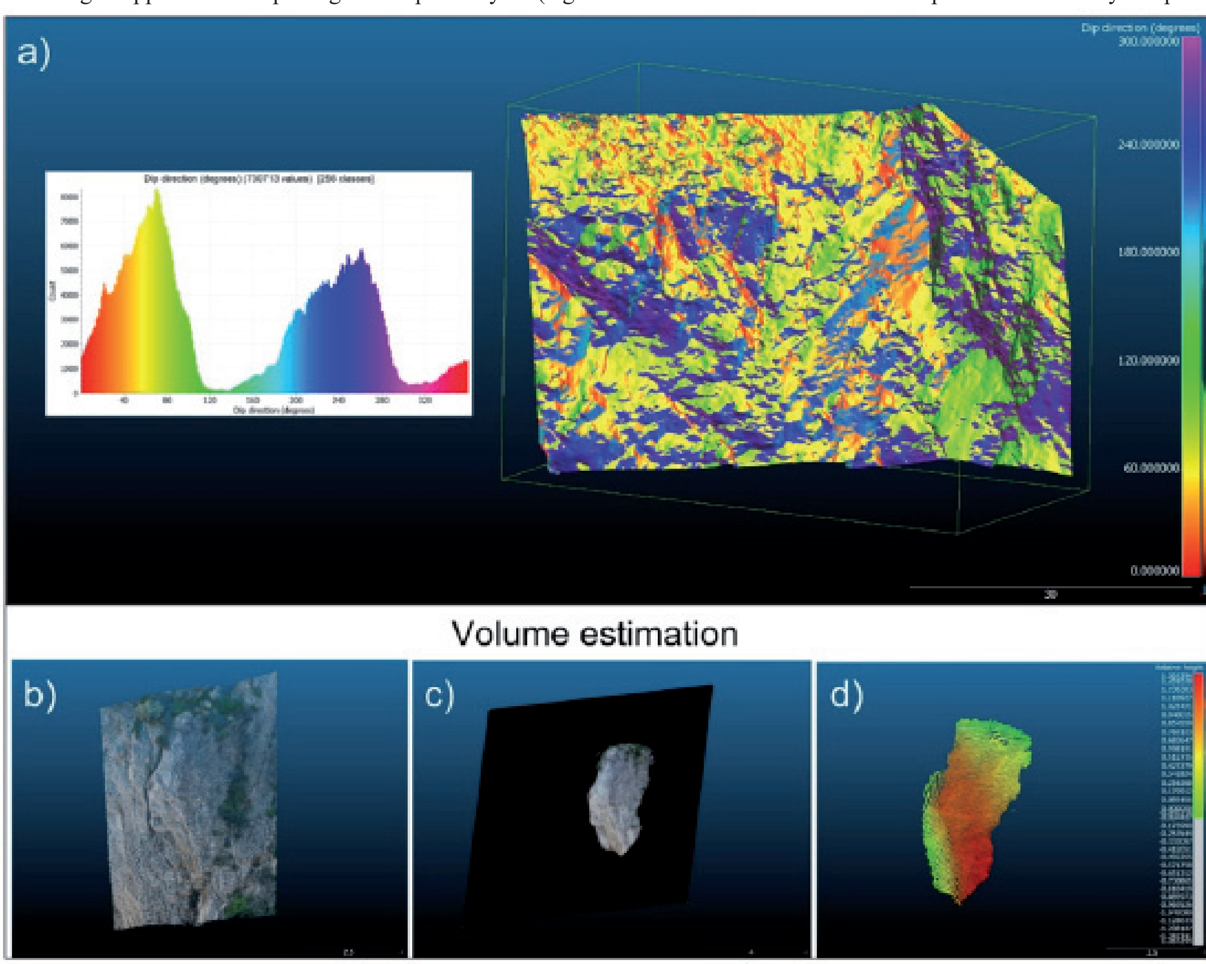

Fig. 3 - Outcomes of the discontinuity extraction by the scalar field approach in a segment of the rock mass (a); Isolated block overhanging the point cloud (b); Discontinuity plane on which the block slides (c); Volumetric calculation in terms of relative difference between different elements (d)

	Discontinuity set	Dip/Dip direction
Sector 1	J1	77/079
	J2	71/045
	J3	76/250
	J4	79/001
	J8	43/038
	J10	81/146
	B	35/271
Sector 2	J1	77/078
	J2	79/050
	J3	78/260
	J4	73/359
	J5	80/233
	J6	50/196
	J8	50/016
	J10	79/156
Sector 3	J1	77/074
	J2	75/047
	J3	75/249
	J4	79/008
	J5	77/220
	J7	74/193
	B	23/256

Tab. 1 - List of kinematic patterns detected in the three different sectors

similar orientation, which are parameterized by means of a color scale allowing the graphical identification of a discontinuity plane. This calculation was carried out by assigning to the point cloud a new scalar field associated with the value of Dip / Dip Direction (Fig. 3a). Each point is assumed as a small surface with a known spatial attitude. The results were derived through a semiautomatic methodology, which involves filtering out on a histogram the statistically most redundant dip directions in terms of point density, which were isolated on the point cloud, exported and reprojected on a stereogram. Three macro reference measurement windows were identified for the extraction of spatial discontinuity data, named Sector 1, 2 and 3. This was aimed at both identifying homogeneous rock mass sectors, in terms of slope orientation, and avoiding very large surveying areas, where the statistical extraction of discontinuities could have been less detailed.

Seven and eight discontinuity sets were statistically recognized at sectors 1-3 and 2, respectively, (Tab. 1). In sector 1, 234 spatial values were extracted using a semiautomatic approach described in the previous chapter in which in (Fig. 3a) the differently colored areas represent the statistical pole concentrations calculated through Fisher's distribution (Fisher, 1950). This approach made it possible to identify the main discontinuity systems (Tab. 1), which intersect giving rise to polyhedral rock volumes of various shapes and sizes. In Sectors 2 and 3, 244 and 217 discontinuity values were extracted, respectively (Tab. 1). The results show that some sets of discontinuities, such as J1, J2, J3 and J4, occur systematically in all the three analysed sectors (Fig. 2). These are related to the main NW-SE trending regional fault systems crossing the studied promontory and the direct N-S faults developing in the westernmost sector of the study area. From a kinematic point of view, all the surveyed rock mass sectors exhibit instability characteristics due to the geometric unfavorability between the slope wall and the orientation of the discontinuities. Three different failure patterns were identified: planar sliding involving 14.96% of critical poles on the total extracted ones at sector 1, 13.11% and 11.98% at sectors 2 and 3, respectively. As for wedge sliding, critical poles represent the 19.05% of the total surveyed at sector 1, while at sectors 2 and 3 these are 35.71% and 33.33%. Flexural toppling affects 30.77% of poles at sector 1, 26.23% at sectors 2, and 18.89% at sector 3. Once all possible unstable kinematic patterns of the rock mass were identified and verified in the field by spot checks on the rock wall, the 3D model was further analysed through the "Compute 2.5D volume" tool implemented in the CloudCompare software, for a quantitative rock volume estimation (Fig. 3b, c, d). In order to estimate their average volume, a series of blocks were isolated on the digital model of the rock mass. The results extracted on numerous projecting blocks scattered evenly over the three sectors of the entire digital cliff model showed volumetric variation within a range from a minimum of 0.02 m^3 to a maximum of 16 m^3.

STABILITY ANALYSIS

The limit equilibrium method (LEM) (Hoek & Bray, 1981) quantifies the stability of a slope through the use of a numerical

Sector	Planar Sliding	Wedge sliding	Flexural Toppling
		Kinematically unstable sets	
1	B, J3	J3 vs J10/ B vs J10/ B vs J4/ J3 vs J1	J1, J2, J8
2	J1, J2	J5 vs J1/ J5 vs J6/ J4 vs J1/ J4 vs J10/ J2 vs J10/ J1 vs J6	J3, J5
3	J1, J2	J7 vs J1/ J7 vs J2/ J5 vs J1/ J5 vs J2/ J1 vs J2/ J1 vs J4/ J2 vs J4	J3, J5

Tab. 2 - List of the discontinuity sets extracted by the scalar field approach

	Planar Sliding	Deterministic		Probabilistic	
Sector	Discontinuity set	FoS static	FoS dynamic	PoF static	PoF dynamic
1	B	0.82	0.66	0.71	0.95
	J3	0.14	0.08	-	-
2	J1	0.13	0.06	-	-
3	J1	0.13	0.06	-	-

Tab. 3 - Calculated safety factor (FoS) and the related probability of failure (PoF) for planar sliding both in static and dynamic conditions

	Flexural Toppling	Deterministic		Probabilistic	
Sector	Discontinuity set	FoS static	FoS dynamic	PoF static	PoF dynamic
1	J1	0.40	-	-	-
	J2	0.62			
2	J3	0.52	-	-	-
	J5	0.51			
3	J3	0.56	-	-	-

Tab. 4 - Calculated safety factor (FoS) and the related probability of failure (PoF) for flexural toppling both in static and dynamic conditions

	Wedge Sliding	Deterministic		Probabilistic	
Sector	Discontinuity set	FoS static	FoS dynamic	PoF static	PoF dynamic
1	J3 - J10	0.30	0.27	0.87	0.98
	B – J 10	1.51	1.25	0.78	0.66
	J4- B	0.82	0.69	0.82	0.69
2	J5 vs J1	0.13	0.12	0.13	0.12
	J5 VS J6	1.46	1.25	0.52	0.46
3	J7 - J2	1.41	1.22	0.33	0.44
	J5 - J1	1.25	1.10	0.31	0.34
	J7 - J1	0.53	0.47	0.95	0.97

Tab. 5 - Calculated safety factor (FoS) and the related probability of failure (PoF) for wedge sliding both in static and dynamic conditions.

coefficient, called the factor of safety (FoS), which represents the ratio of the resisting forces to the destabilizing forces, acting along a previously assumed failure surface. Values lower than 1 indicate instability. The use of remote sensing techniques, with the subsequent digital outcrop development, improved the results of the analysis, as it was possible to accurately derive the input data required by the software, such as slope height, the angle of each joint and their relative spacing. The calculation was performed herein under both static and dynamic conditions by considering, in this latter case, the seismic coefficient affecting the study area.

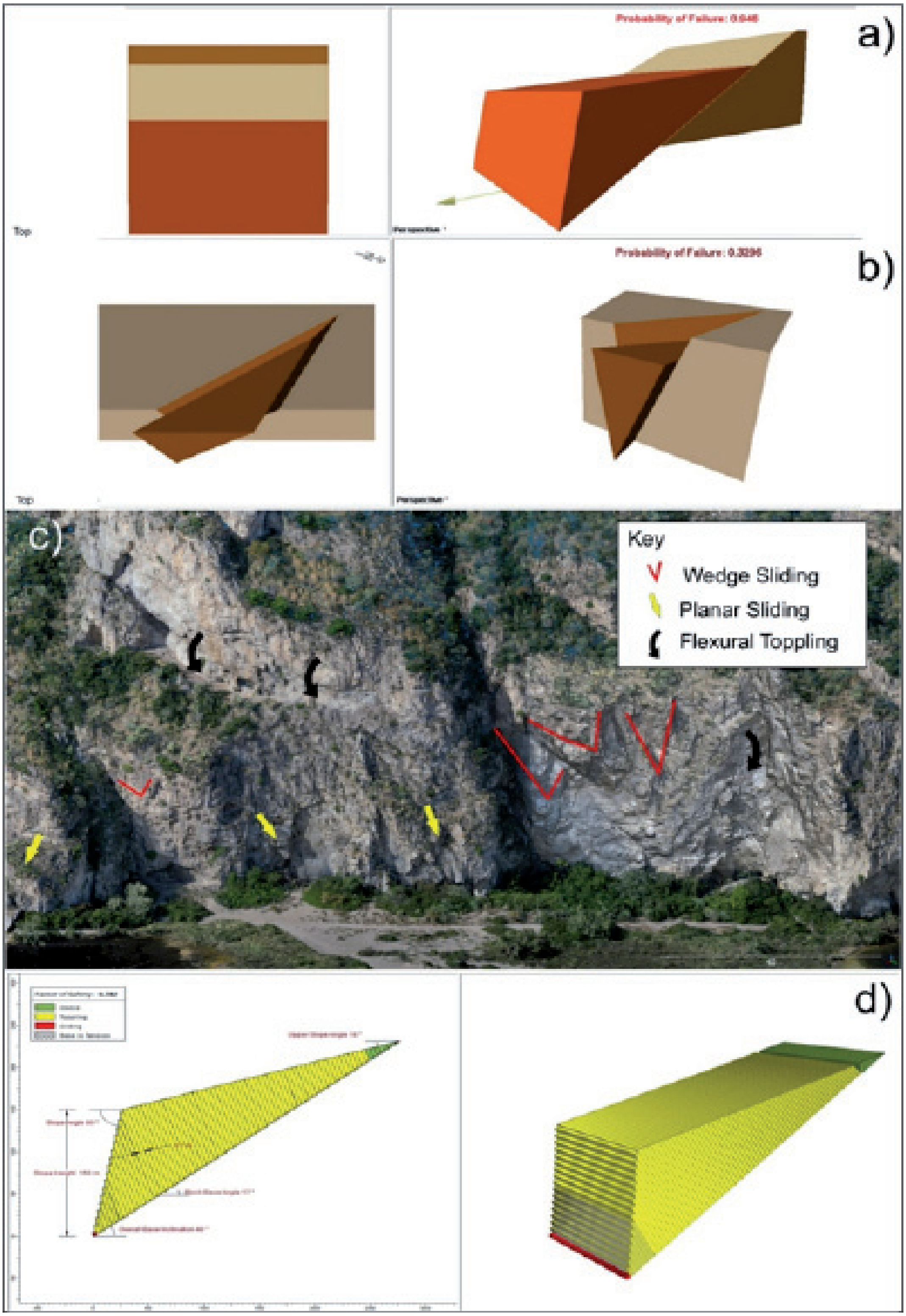

Fig. 4 - Summary of FoS calculation with Rocscience software for the three kinematic patterns calculated in the stability analysis: Simulation for planar sliding (a); Simulation for wedge sliding (b); Framing of potential kinematics identified on the point cloud (c); Simulation for direct toppling (d)

The stability analysis against the three different kinematic failure patterns was carried out by using Rocscience RocPlane, RocTopple and SWedge programs (Fig. 4), with respect to the deterministic and probabilistic calculations under both static and dynamic conditions (Tab. 3, 4, 5). The calculated factors of safety, show a predisposing instability for planar sliding and flexural toppling with FoS of 0.5 in most cases, while wedge sliding shows a variability of values; in this case, some asymmetric wedges are characterized by stable FoS values. Overall, the analysis showed unstable FoS values for all three kinematic failure patterns, with a probability of failure ranging from a minimum of 0.069 to a maximum of 1 under dynamic condition.

DISCUSSIONS AND FINAL REMARKS

In this work. the analysis of a digital outcrop model. reconstructed by means of aerial photogrammetry. was presented as a rapid survey procedure to characterize a rock mass located within the “Laghetti di Marinello” nature reserve. in order to improve the classic field measurements. limited by poor accessibility and relatively long acquisition times of geostructural data. Using the high detail of the dense point cloud of rock masses obtained. the quantitative extraction of the spatial orientations of the main discontinuities was carried out. which highlighted the redundant presence of certain sets of discontinuities in all three sectors analysed. some of which characterized by orientations similar to the major tectonic structures present in the study area. Once data were extracted and validated in the field. through a series of conventional measurement. their statistical processing and kinematic analysis highlighted. among the potential failure modes. the possibility of planar sliding. wedge sliding and flexural toppling. All these failure patterns are characterized by low safety factors. calculated herein according to the limit equilibrium method. and by a high probability of failure. Among the analyses carried out on the digital model. great importance goes to the estimation of a dimensional range in terms of volumes which from the results shows values ranging from a minimum of 0.02 m^3 to a maximum of 16 m^3 of protruding blocks that are likely to be mobilized in future events. This highlights the hazard threatening the safe use of the natural paths crossing the reserve. focusing attention on the need of planning mitigation measures.

As a final consideration. the remote survey methodology using aerial photogrammetry allows the advantages of surveying large portions of rock mass compared to the traditional survey. with the possibility of a quick measurement of a large number of discontinuity data homogeneously on the entire cliff. Thus allowing a reliable estimate of unstable rock volumes directly on the digital model. Moreover. further new surveys could guarantee the monitoring of the rock mass over time. making aerial photogrammetry a useful tool for the management of nature reserves or protected areas in general.

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