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FROM SURVEY TO ANALYSIS AND VISUALIZATION METHODS, NEW APPROACHES TO DEFINE ROCKFALL HAZARD

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EXTENDED ABSTRACT

Nell'ultimo decennio l'approccio allo studio dei fenomeni franosi è molto cambiato. L'avanzamento tecnologico che ha interessato sia i metodi di rilievo che quelli di elaborazione del dato ha permesso di affrontare le tematiche del rischio idrogeologico in maniera più approfondita e dettagliata.

Nello specifico, per quanto riguarda i sistemi di rilievo abbiamo assistito negli ultimi anni all'avvento e l'evoluzione dei sistemi a pilotaggio remoto che permetto di effettuare sia rilievi fotogrammetrici che laser, anche in aree altrimenti non raggiungibili. Molto più recentemente gli stessi sistemi fotogrammetrici e laser hanno trovato applicazione anche attraverso l'utilizzo di semplici smartphone e tablet, dotati di camere molto evolute e sistemi LiDAR.

Di pari passo all'avvento di questi nuovi sistemi di rilievo, anche i software di analisi e di visualizzazione/mappatura del dato geologico e ingegneristico hanno subito un avanzamento notevole. Per quanto riguarda i software di analisi, è possibile oggigiorno poter contare su una scelta molto più ambia ed su interfacce sempre più user-friendly. Le tecniche di mappatura e visualizzazione invece hanno visto l'evoluzione più recente nei sistemi di realtà virtuale ed aumentata che hanno completamente rivoluzionato il modo di visualizzare e interpretare il dato geologico.

In questo contesto, il presente lavoro mostra l'applicazione di questi sistemi innovativi di rilievo, analisi e visualizzazione del dato geologico nel caso di studio del Monte Conero (AN), nella Regione Marche. Il Monte Conero è un promontorio costiero che raggiunge un'altezza massima di circa 572 m s.l.m. ed è caratterizzato da versanti molto acclivi nel suo lato orientale, creando spettacolari falesie sul Mare Adriatico, e versanti più dolci verso occidente. Dal punto di vista geologico, il promontorio del Monte Conero, che ricade nel Foglio 293 Osimo della nuova Carta Geologica d'Italia in scala 1: 50.000, è costituito da un'anticlinale asimmetrica a vergenza E – NE con una direzione assiale media di N 138°; il versante a mare, che coincide con il fianco esterno della piega stessa, immerge verso E – NE con un dip angle di 75° - 80°, mentre quello occidentale ha un'inclinazione media di 22° (Cello & Coppola, 1984). Le formazioni geologiche affioranti nell'area appartengono alla Successione Umbro Marchigiana e vanno dal Giurassico Superiore (Formazione della Maioloica) al Miocene (Schlier). Dalla formazione più antica alla più recente queste sono: Maiolica, Marne a Fucoidi, Scaglia Rossa, Scaglia Variegata, Scaglia Cinerea e Schlier.

Le caratteristiche geologiche, morfologiche, faunistiche e paesaggistiche fanno del Monte Conero uno dei Parchi più belli della costa Adriatica, attirando ogni anno un numero considerevole di turisti da tutto il mondo. Le stesse caratteristiche geologiche e morfologiche che lo rendono un attrazione turistica molto importante hanno un notevole impatto anche dal punto di vista del rischio idrogeologico. Infatti, le acclivi falesie nel lato orientale del promontorio sono spesso interessate da fenomeni franosi che, soprattutto durante la stagione estiva, possono essere un rischio per escursionisti e turisti. In questo lavoro mostreremo lo studio del rischio idrogeologico attraverso diverse tecniche di rilievo, analisi e visualizzazione del dato. Nello specifico sarà analizzata l'area del sentiero escursionistico chiamato "Passo del Lupo", che da tempo è chiuso per rischio di crolli. Sarà evidenziato come l'utilizzo integrato di sistemi LiDAR aerei e terrestri (tramite Tablet), droni e realtà aumentata possa giocare un ruolo chiave nella definizione di modelli geologici più dettagliati da utilizzare all'interno di simulazioni di caduta massi.

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ABSTRACT

Rockfalls are among the most dangerous natural hazards. The study of these phenomena may be complex in relation to the geology and the rock mass characteristics. Recent advances on the use of remote sensing techniques made the survey of rock slopes easier and faster, increasing the amount and quality of data. At the same time, the improved availability of software for characterizing rock slopes and simulating rockfalls permits a more detailed and precise definition of rockfall hazard areas.

In this context, this research highlights the importance of using remote sensing techniques in the study of these phenomena, especially in developing accurate and reliable geological and structural models.

The Regional Park of Monte Conero (Ancona, Italy) is used as the case example. The study area has been investigated through conventional geological/structural surveys, UAV photogrammetry and iPad-based LiDAR. The data gathered from surveys have been used to perform rockfall simulations and define potential mitigation measures. Finally, innovative visualization techniques based on the use of Virtual Reality will be introduced for an improved interpretation of geological and structural data and simulation results.

***Keywords**: UAV, Rockfall simulation, geological model, augmented reality.*

INTRODUCTION

The approach to the survey and analysis of landslides has remarkably changed in the last two decades. The technological advancement has led to the use of innovative survey techniques, data processing and visualization. Terrestrial and aerial LiDAR (Light Detection and Ranging o Laser Imaging Detection) and Unmanned Aerial Vehicle (UAV) are nowadays among the most used instrumentations when dealing with steep slopes and/or inaccessible areas. These techniques give the opportunity to collect a large amount of data to be used for data analysis and interpretation.

Some example of the use of the technique, among others, have been recently given by Tavasci *et alii* (2023), that showed the analysis of the Rock Pinnacle "Campanile di Val Montanaia" (Friuli-Venezia Giulia , Northern Italy) through the integration of geomatic and geomechanical data. A similar survey approach has been reported by Caliò *et alii* (2023) for evaluating the rockfall magnitude in poorly accessible cliffs at the Marinello Lakes nature reserve (Sicily, Southern Italy) through both photogrammetric and infrared thermography techniques.

The possibility to improve the amount and quality of data through these survey techniques is very important prior to the interpretation of geological and structural features and the analysis of slopes. For example, Mammoliti *et alii* (2023) shows the potential use of UAV data and tracer test to develop reliable Discerte Fracture Network models. A similar analysis combining UAV data and Discrete Fracture Network model was carried out by Francioni *et alii*, (2020) to improve the quality of rockfall simulation at the Scanno Landslide (in the Abruzzi region of Italy). Remote sensing data can also play a key role in understanding the failure mechanisms of large rock avalanche, as demonstrated by Donati *et alii* (2021), that used pre-failure and post-failure remote sensing data to constrain three-dimensional numerical modelling of the Hope Slide (Canada).

A review of the most used survey and analysis techniques in the study of rock slopes has been presented by Francioni *et alii* (2021), highlighting limitation and advantage of each one of them.

It is clear that the technological advances presented by all these authors let to improved landslide/rockslide analyses. It is important to highlight the geological and structural knowledge of the investigated areas still represent the most important aspect for reliable studies. Remote sensing data must be interpreted taking into account the geological and structural evolution of the study area to avoid misinterpretation of data. In this context, this research shows the combined use of innovative remote sensing techniques and rockfall analysis, highlighting the importance of geological and structural model in the simulation results. The case study used to this purpose is the Conero Regional Park in the Marche Region, Central Italy.

Conventional geomechanical surveys were integrated with UAV photogrammetry and iPad based LiDAR to improve the understanding of structural setting. The morphology of the areas was tridimensional recreated through aerial LiDAR data while soil cover was interpreted though field survey and orthophotos. The integration of these techniques played a key role in the rockfall analysis carried out to define rockfall hazard areas and suggest potential mitigation measures.

STUDY AREA

In this study we have investigated the area of the "Passo del Lupo" trail, located in the promontory of the Monte Conero, in the Conero Regional Park (Central Italy, Figure 1a).

This trail was, in the past, an important touristic attraction, representing the only way to reach the beach "Spiaggia delle due Sorelle," a wonderful pocket beach in the Adriatic sea. Unfortunately, due to the frequent rockfall events and the dangerousness of the trail, this was closed several years ago, and the beach is now only accessible though boats. The Monte Conero (572 m a.s.l.) is an active cliff with multiple types of instability phenomena (Fruzzatti *et alii*, 2011; Fullin *et alii*, 2023). The coastal area is characterized by steep cliffs with an average height usually higher than 100 m a.s.l. From a geological point of view, the Monte Conero is an open NE verging asymmetric anticline. The fold axis are often intersected by a strike-slip fault system mainly oriented E–W, and the exhibit an average orientation of 138° with a NE limb dipping between

70° and 85° and a SW limb dipping approximately 20° (Cello & Coppola, 1989; Pierantoni *et alii*, 2013). The geological formations outcropping in the area (Figure 1b) belongs to the Umbria-Marche stratigraphic succession and range from Cretaceous (Maiolica and Marne a Fucoidi Fms.) to the Eocene marly limestones (Scaglia Rossa Fm.).

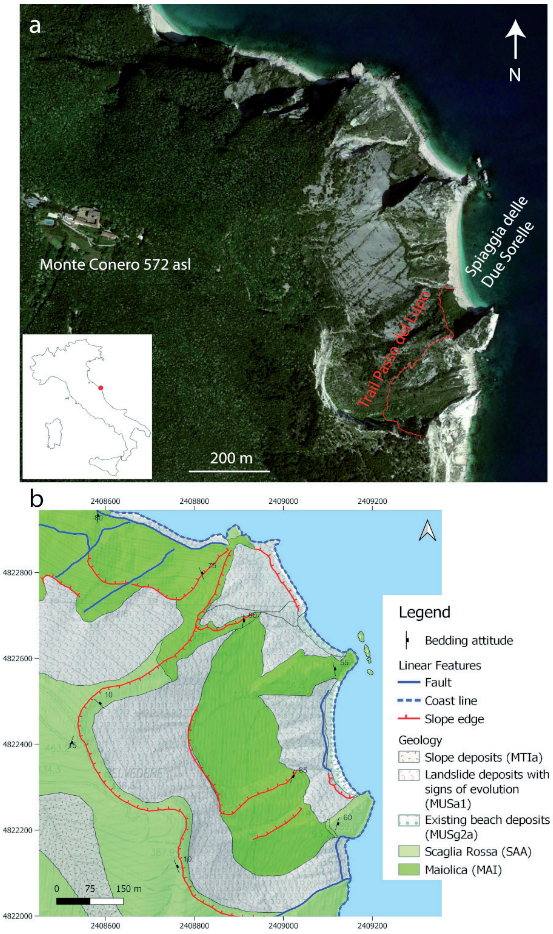

Fig. 1 - a) Study area with highlighted the Passo del Lupo trail (red line) and the Spiaggia delle due Sorelle beach. B) Geological map of the study area

METHODS

The study area was investigated using different survey techniques. Conventional geomechanical surveys were conducted in the accessible area following the procedures proposed by the International Society for Rock Mechanics (ISRM, 1978). These were integrated with ground-based LiDAR which was undertaken with a tablet iPad Pro. The scans were carried out in some representative outcrops along the trail with the goal of extracting the 3D models to be used in lab for more accurate analysis of rock mass. During the survey, the iPad Pro was held by the operator (trying to keep it as stable as possible) at a distance from the slope of ca 1 m.

Through the geomechanical analysis it was possible to define rock mass characteristics, including rock block volumes and shape. Due to the inaccessibility of most of the area under study, conventional geomechanical and ground-based LiDAR surveys were integrated with aerial LiDAR and UAV photogrammetry. The aerial LiDAR of Conero Regional Park is available through the Ministero dell'Ambiente e della Tutela del Territorio e del Mare and has a resolution of 2×2 m. This was used for the development of Digital Elevation Model (DEM) and GIS thematic maps. Regarding the UAV survey, this was undertaken in the whole study area to extract 3D virtual outcrop models. A Mavic 2 Pro drone was used for the survey. This is equipped with a 20-megapixel camera resolution with the following characteristics: 28 mm focal length with f/2.8 to f/11 aperture and maximum image size of 5472×3648 px. Due to complex morphological characteristics of the area, the UAV was flight using manual mode. Photographs were taken from an average distance ranging from 70 to 120 m from outcrops. Side and frontal overlap was kept ca 70-80%. Structure from Motion (SfM) based software Agisoft Metashape was used to manage the UAV photographs. Agisoft Metashape is a software developed for photogrammetric processing of digital images, able to generates 3D spatial data which can be used in different fields such as GIS applications, rock-mechanics, archeology, cultural heritage, etc. In this case, the software allowed to reconstruct a 3D model and orthophotos of the study area. These datasets were then used for the identification of soil covers in inaccessible areas and for improving the geomechanical interpretation of the steep and inaccessible slopes. The information gathered from LiDAR extracted thematic maps and geomechanical analyses (both from conventional and remote sensing surveys) were utilized to perform rockfall simulations. The combined deterministic/probabilistic approach implemented in the RockyFor3D software (Dorren & Simoni, 2014) was used for this purpose. Rockyfor3D™ is a rigid-body impact code that calculates trajectories of single falling rock blocks of definite geometry. The input parameters considered for the simulation are: release location, density, shape and dimensions of rock blocks, local slope surface roughness and coefficient of restitution. These are assigned to the digital surface model through GIS processing. The local slope surface roughness is represented by a parameter defined as maximum obstacle height and is quantified by statistical classes, namely rg70%, rg20%, and rg10% (Dorren & Simoni, 2014) and can be assigned in relation to the soil cover. LiDAR extracted DEM (with resolution of 2×2 m) was used for the simulation. Rock block density was set to 2,500 kg/m^3 and, for each source cell, a total of 100 block-run were considered. The rock block volume was derived by the analysis of past rockfall events and geomechanical analysis. Different simulations were undertaken using the different potential block volumes.

Finally, the UAV extracted 3D models and the results of the analysis were included in a virtual database and used for Augmented Reality (AR) based analyses. The AR model was created using the Campfire3d software (https://www.campfire3d.com/) and the data was visualized through the Meta Quest 3 headset. Through this technique it was possible to undertake an improved visualization and interpretation of geological features and analysis results.

RESULTS AND DISCUSSION

The geomechanical data gathered from conventional surveys and ground-based LiDAR highlighted three main discontinuity sets oriented E-W, NE-SW and NW-SE, with the NW-SE being the bedding planes. This agrees with previous studies presented by Mammoliti *et alii* (2022) and Marmoni *et alii* (2022).

The bedding spacing measured in the Scaglia Rossa Fm vary between few to 30 cm. The other two joint sets have a similar spacing, ranging between 5 and 30 cm. The maximum block volume calculated using the discontinuity spacing was 0.027 m^3. Block with similar volumes (previously failed from the slope), were identified during the surveys, confirming the results of geomechanical data analysis. However, blocks with higher volumes were also identified in proximity of the trail and in the orthophotos. The volumes of these blocks, ranging from 5 to 12 m^3, were in contrast with the evidence resulting from the ground geomechanical study. Therefore, the geomechanical data gathered in the accessible areas through ground survey were integrated with the analysis of UAV models. Figure 2 shows an example of discontinuities interpretation carried out through the UAV photogrammetric models.

Furthermore, it was possible to observe that, in the upper part of the slope, the Scaglia Rossa Fm presents different characteristics. The spacing of bedding planes remarkably change, reaching values up to 3 m (Figure 3). The presence of these "mega beds" within the Scaglia Rossa Fm was documented in the past by other authors (Coccioni *et alii*, 1989) and interpreted as torbiditic units. The analysis of these units played a fundamental role in the subsequent rockfall analysis since it remarkably changed the potential rock block volumes (in this unit the potential block volume was calculated around 12 m^3). Once defined the main geomechanical characteristics of rock mass, the rockfall simulations have been performed. Rockfall source areas were defined from "Slope" thematic map (map representing the slope steepness), extracted by the LiDAR data. The UAV extracted orthophoto and google earth images were utilized for the development of soil cover map, represented in Figure 4. Six different soil types were interpreted: a) source area, b) beach sediments, c) bedrock (in the Maiolica Fm), d) bedrock with vegetation, e) talus slope, f) vegetated area. The surface roughness parameters rg70%, rg70%, and rg10% were selected according with Dorren (2016) and reported in Table 1. Vegetated area (Figure 4) is not included since it is outside of the simulation area.

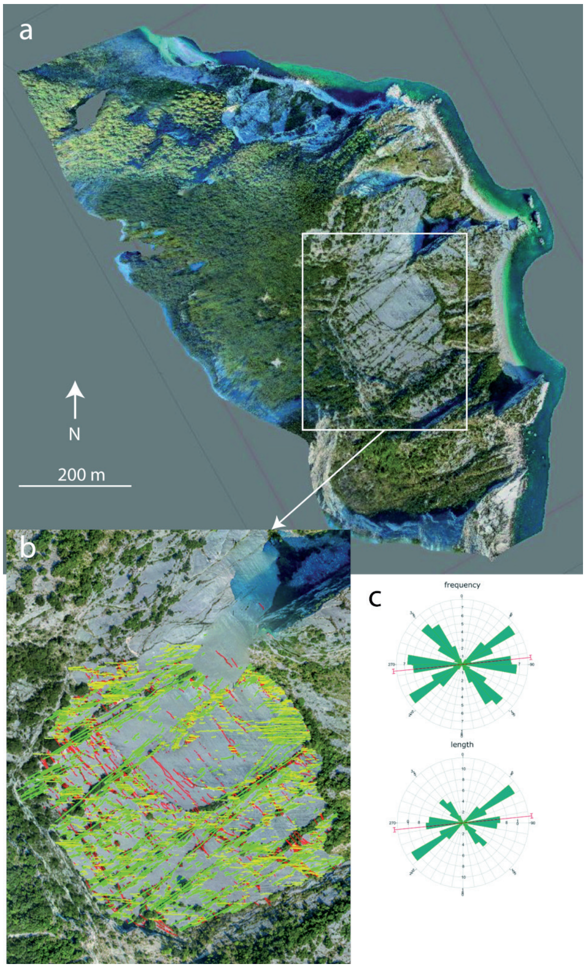

Fig. 2 - a) 3D UAV model. b) Geomechanical interpretation of UAV model. c) Orientation of the three discontinuity sets identified

Soil cover	rg70	rg20	rg10	Soil type
Source area	0	0	0.05	6
bedrock	0	0	0	7
bedrock with vegetation	0	0.5	0.1	5
talus slope	0.15	0.15	0.25	4
beach sediments	0.03	0.05	0.05	3

Tab. 1 - Surface roughness parameters used during the rockfall simulations

With the goal of highlighting the importance of geomechanical and geological interpretation of the area, the rockfall simulations were performed using both the block volumes of 0.027 m^3 and 12 m^3, respectively. The location of the barrier was defined using a trial-error approach while the absorption energy was set to 100 kJ. In Figures 5a and b, it is possible to observe the simulation carried out using a block volume of 0.027 m^3 without (a) and with (b) mitigation works (rock fall barriers).

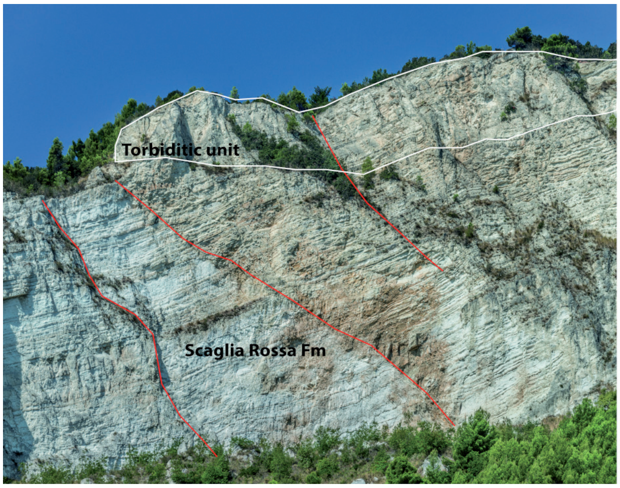

Fig. 3 - Torbiditic unit identified within the Scaglia Rossa Fm

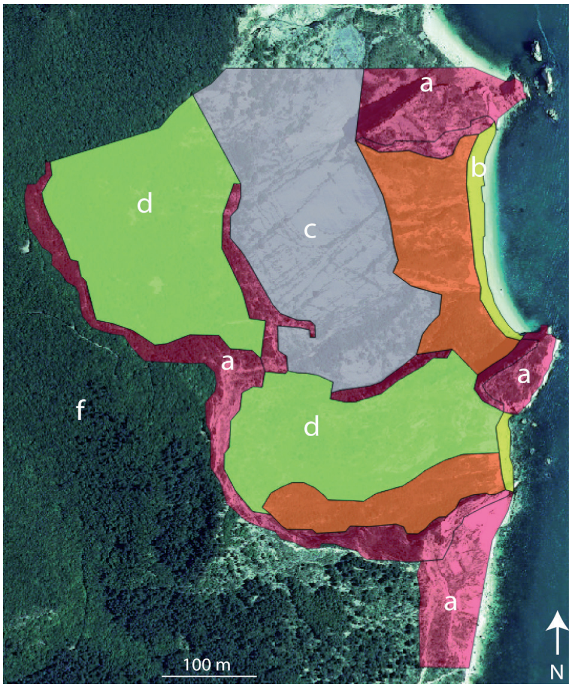

Fig. 4 - Six different soil types interpreted in the study area: a) source area, b) beach sediments, c) bedrock (in the Maiolica Fm), d) bedrock with vegetation, e) talus slope, f) vegetated area. Red line represents the Passo del Lupo trail

The results are shown in terms of block reach probability. The reach probability areas of Figure 5a have been compared with the areas where blocks of similar dimension where surveyed to validate the simulation, obtaining a good correlation between the two. It is possible to observe in Figure 5b that the rockfall barriers stop the blocks failing from the source areas, securing the trail. The scenario, however, is completely different when using the 12 m^3 block volume, with a kinetic energy that remarkably invrease.

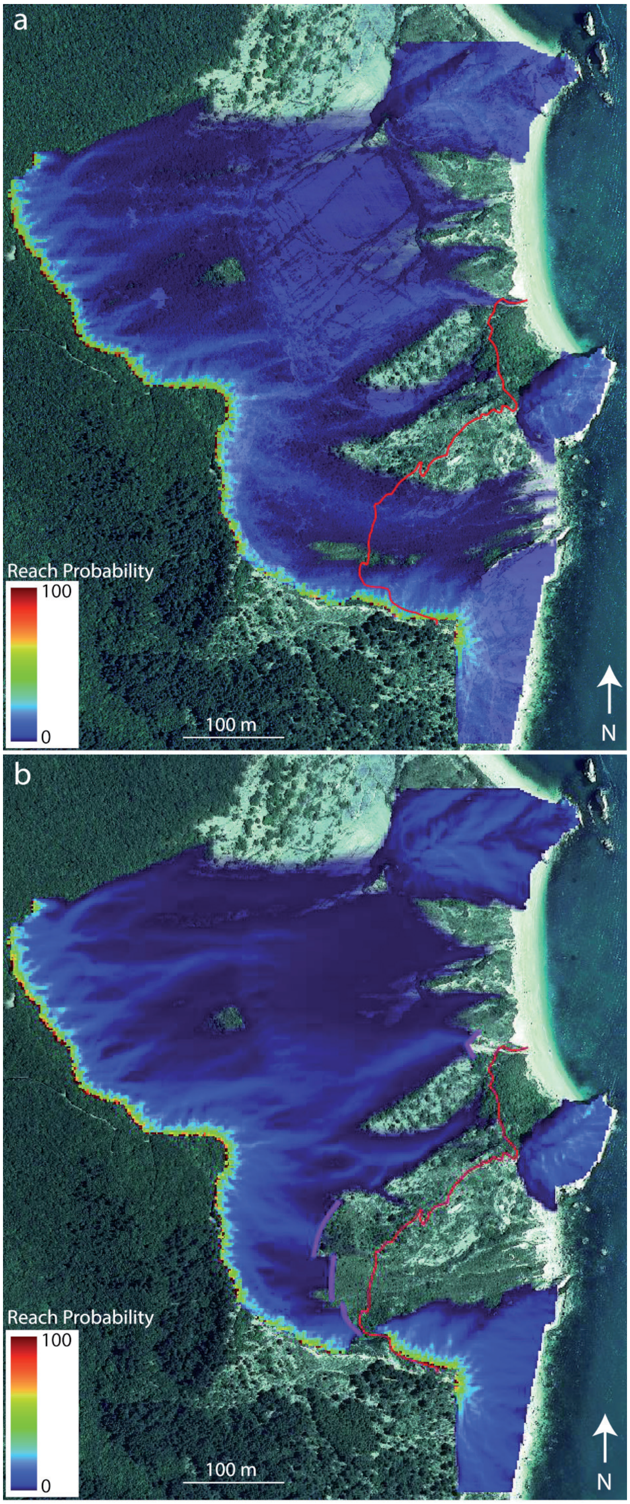

Fig. 5 - Rockfall simulation carried out using a block volume of 0.027 m^3 without (a) and with (b) mitigation works. Red line represents the Passo del Lupo trail while reddish-purple lines the mitigation works

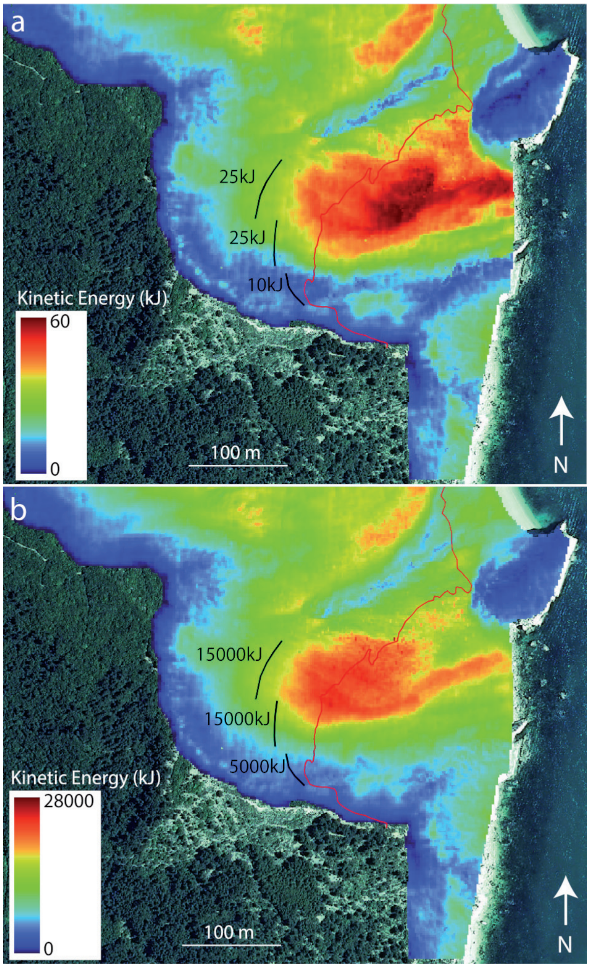

Fig. 6 - Map of rock blocks kinetic energy. Black numbers indicate the kinetic energy in proximity of rockfall barriers (black lines). Red line represents the Passo del Lupo trail

Figures 6a and b show the simulation using 0.027 m^3 and 12 m^3, respectively. It is possible to see that the kinetic energy of blocks in proximity of rockfall barriers varies from values lower than 100 kJ in the first simulation (a) to values close to 15,000 kJ in the second one (b). With such as kinetic energy the mitigation strategy completely changes, introducing the possibility to use different types of mitigation measures, e.g. the combination of active and passive mitigation solution.

Finally, the 3D model of the Monte Conero promontory was included in a virtual database to be used for improved AR interpretation and analysis of the promontory. This methodology represents the last innovation in the field of data visualization and can be very important for the interpretation of geological feature and for risk mitigation strategies (Donati *et alii*, 2023). An example of improved AR analysis and interpretation is reported in Figure 7, where it is possible to see two PhD students of the University of Urbino analyzing the study area. The AR model of the Monte Conero is now being used also for teaching applications at University of Urbino. In the near future, this research team will be leading two research projects, the PRIN 2022 and Interreg VI A Italy - Croatia 2021-2027, to further develop the use of AR in geoscience, enhancing risk management strategies and environmental and tourism applications.

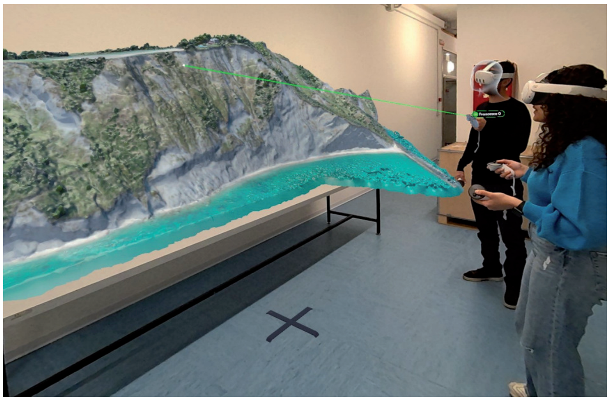

Fig. 7 - Analysis and interpretation of AR model of the Monte Conero promontory at University of Urbino

CONCLUSION

The Passo del Lupo trail is a touristic trail connecting the Conero Regional Park with the beach Spiaggia delle due Sorelle. The trail has been closed years ago due to its dangerousness. In this study we presented a multidisciplinary analysis for the study of rockfall hazard along the trail. The combined use of conventional and remote sensing surveys was important to improve the amount and quality of data. LiDAR data with 2×2 m resolution was used as base for rockfall simulation and for developing thematic maps. iPad LiDAR was used along the trail to create 3D model of the most representative outcrops and improve conventional geomechanical data. The inaccessible areas and steep slopes were finally surveyed using UAV. In particular, the UAV extracted model played a key role in the identification of a torbiditic unit within the Scaglia Rossa Fm. This unit is characterized by values of bedding spacing much higher than the one measured during the ground surveys. The volume of blocks has been calculated around 0.027 m^3 during the ground surveys, and 12 m^3 in the torbiditic unit. This resulted in a potentially larger kinematic energy of the block failing from the slope. The rockfall simulations carried out using both block volumes highlighted how the mitigation strategies completely change in the two different geological contexts, pointing out the crucial importance of a good geological interpretation of the study area. Finally, we have introduced the use of AR to improve data interpretation and visualization. This technique represents the latest innovation in terms of data visualization and could be used for many other applications in the future, such as risk mitigation strategies, tourism, etc. In this study the team of University of Urbino has used the AR model to improve the interpretation of geological features and data analysis and is now enhancing the use of AR for teaching purposes.

REFERENCES

Caliò D., Mineo S. & Pappalardo G. (2023) - *Digital Rock Mass Analysis for the Evaluation of Rockfall Magnitude at Poorly Accessible Cliffs.* Remote Sensing, **15**(6):1515. https://doi.org/10.3390/rs15061515.

Cello G. & Coppola L. (1989) - *Modalità e stili deformativi nell'area anconetana.* Stud. Geol. Camerti, **XI**: 37-47 pp.

Coccioni R., Moretti E., Nesci O., Savelli D., Tramontana M., Veneri F. & Astracedi M. (1993) - *Carta Geologica con itinerari escursionistici, scala 1:20.000. Parco Regionale del Conero,* S.E.L.C.A., Firenze, Italia

Coccioni R., Franchi R., Nesci O., Wezel F.C., Battistini F. & Pallecchi P. (1989) - *Stratigraphy and mineralogy of the Selli Level (early Aptian) at the base of the Marne a Fucoidi in the Umbro-Marchean Apennines, Italy*. J. Wiedmann (Ed.), Cretaceous of the Western Tethys: 563-584.

Donati D., Stead D., Onsel E., Mysiorek J. & Chang O. (2023) -*Remote Sensing and Geovisualization of Rock Slopes and Landslides*. Remote Sens., **15**: 3702. https://doi.org/10.3390/rs15153702.

Donati D., Stead D., Brideau M.A. & Ghirotti M. (2021) - *Using pre-failure and post-failure remote sensing data to constrain the three-dimensional numerical model of a large rock slope failure.* Landslides, **18**(3): 827-847.

Dorren L.K.A. (2016) - *Rockyfor3D (v5.2) revealed – Transparent description of the complete 3D rockfall model*. EcorisQ paper (www.ecorisq.org): 32 pp.

Dorren L. K. A. & Simoni S. (2014) - *Rockyfor3D (v 5.1) – Rivelato -Descrizione Trasparente del Modello 3D di Caduta Massi*. EcorisQ. Ginevra, Switzerland.

Francioni M., Calamita F. & Sciarra N. (2021) - *The Evolution Of Methods For The Survey And Analysis Of Rock Slopes: A Review.* Italian Journal of Engineering Geology and Environment. Special Issue vol.**1**: 87-95.

Francioni M., Antonaci F., Sciarra N., Robiati C., Coggan J., Stead D. & Calamita F. (2020) - *Application of unmanned aerial vehicle data and discrete fracture network models for improved rockfall simulations.* Remote Sens., **12**(12): 2053. https://doi.org/10.3390/rs12122053

Fullin N., Duo E., Fabbri S., Francioni M., Ghirotti M. & Ciavola P. (2023) - *Quantitative Characterization of Coastal Cliff Retreat and Landslide Processes at Portonovo–Trave Cliffs (Conero, Ancona, Italy) Using Multi-Source Remote Sensing Data.* Remote Sens., **15**: 4120. https://doi.org/10.3390/rs15174120

Fruzzetti V. M. E., Segato D., Ruggeri P., Vita A., Sakellariadi E. & Scarpelli G. (2011) - *Fenomeni di instabilità della falesia del Monte Conero: ruolo dell'assetto strutturale.* Incontro Annuale dei Ricercatori di Geotecnica 2011 - IARG 2011. Torino, 4-6 Luglio 2011

Mammoliti E., Pepi A., Fronzi D., Morelli S., Volatili T., Tazioli A. & Francioni M. (2023) - *3D Discrete Fracture Network Modelling from UAV Imagery Coupled with Tracer Tests to Assess Fracture Conductivity in an Unstable Rock Slope: Implications for Rockfall Phenomena.* Remote Sens., **15**: 1222. https://doi.org/10.3390/rs15051222

Marmoni G.M., Martino S., Censi M., Menichetti M., Piacentini D., Scarascia Mugnozza G., Torre D. & Troiani F. (2023) - *Transition from rock mass creep to progressive failure for rockslide initiation at Mt. Conero (Italy),* Geomorphology, **437**: 108750.

Pierantoni P., Deiana G. & Galdenzi S. *Stratigraphic and Structural Features of the Sibillini Mountains (Umbria-Marche Apennines, Italy).* Ital. J. Geosci., **132**: 497-520.

Tavasci L., Lambertini A., Donati D., Girelli V.A., Lattanzi G., Castellaro S., Gandolfi S. & Borgatti L. (2023) - *A laboratory for the integration of geomatic and geomechanical data: The Rock Pinnacle "Campanile di Val Montanaia"*. Remote Sens., **15**: 4854. https://doi.org/10.3390/rs15194854

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