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MULTI-TEMPORAL EVOLUTION ANALYSIS OF MARONTI CLIFF (ISCHIA ISLAND, ITALY) DERIVED FROM MULTI-PERSPECTIVE PHOTOGRAPHIC DATASETS

Luigi PARENTE(*), Jlenia COCCA(*), Davide MAZZA(*), Vincenzo ALBANESE(**), Francesco Maria GUADAGNO(*) & Paola REVELLINO(*)

(*)University of Sannio - Department of Science and Technology - Benevento, Italy
(**)Dipartimento di Protezione Civile - Italy
Corresponding author: geo.luigiparente@gmail.com

EXTENDED ABSTRACT

Il fenomeno dell'erosione costiera può avere forti ripercussioni sul paesaggio e sulle attività socio economiche. Fattori antropici e dinamiche naturali rendono complesso lo studio dei processi erosivi nonché la progettazione di soluzioni finalizzate alla gestione sicura degli ambienti costieri. L'implementazione di attività di geo-monitoraggio multi-temporale è fondamentale al fine di quantificare e analizzare i trend erosivi per poter intervenire in modo efficace sulle aree a maggior rischio. L'utilizzo di tecniche di telerilevamento di prossimità (es. stazioni totali, interferometria radar, fotogrammetria e LiDAR da drone e terrestre) può fornire i dati necessari al monitoraggio delle scogliere.

Di particolare importanza è la valutazione dell'applicabilità e dell'accuratezza dei metodi di rilievo per giungere alla definizione di criteri oggettivi sui quali poter realizzare un programma di monitoraggio e di intervento.

A fronte di queste considerazioni, in questo studio si presenta un approccio all'analisi dell'evoluzione di un tratto di scogliera a medio-lungo termine attraverso l'utilizzo di dati fotografici acquisiti con diversa strumentazione e per scopi diversi. Tra i requisiti tecnici di un programma robusto di monitoraggio di una scogliera vi è la pianificazione dell'acquisizione dei dati secondo una certa tempistica. Questo è particolarmente importante per poter catturare i cambiamenti che avvengono a seguito di piccoli eventi di distacco anche senza disporre di dedicate riprese o misure. Per tale motivo in questo studio si è deciso di testare la bontà di dati fotografici acquisiti non seguendo quelle procedure rigorose tipiche di un rilievo fotogrammetrico finalizzato ad ottenere misure ad alta accuratezza e precisione.

Negli ultimi anni, grazie allo sviluppo e alla diffusione di fotocamere e smartphone sempre più sofisticati in termini di risoluzione e di qualità dell'immagine, è possibile utilizzare dataset di set fotografici acquisiti anche per "turismo" al fine di creare nuove opportunità per lo studio dell'evoluzione costiera. Tali set fotografici sono stati sottoposti ad elaborazioni di tipo fotogrammetrico al fine di generare una serie di risultati tra cui nuvole di punti, modelli digitali del terreno e ortofoto.

Nel presente lavoro, tre dataset datati 2011, 2021 e 2023 sono stati utilizzati per valutare le variazioni di una porzione di scogliera della baia dei Maronti, sull'Isola d'Ischia. I dataset del 2011 e del 2021 sono stati acquisiti da operatori amatoriali attraverso camera digitale e da smartphone rispettivamente. Le immagini acquisite presentano differenze in termini di qualità dovute al diverso tipo di sensore utilizzato. Tuttavia, sono state acquisite da diverse angolazioni, a varie distanze e con una buona percentuale di sovrapposizione permettendo l'elaborazione fotogrammetrica attraverso l'utilizzo degli algoritmi di SFM (*Structure from Motion*).

Le acquisizioni del 2023 sono state, invece, realizzate da operatori esperti del Gruppo di Geologia Applicata e Geomonitoraggio dell'Università degli Studi del Sannio, al fine di generare un modello 3D ad alta risoluzione del sito di studio. Il modello generato dal suddetto dataset è stato georiferito grazie ad un rilievo topografico eseguito preliminarmente alle operazioni di riprese aeree. Questo è stato indispensabile in fase di post-elaborazione fotogrammetrica al fine di orientare e scalare il modello tridimensionale. I modelli del 2011 e del 2021 sono stati allineati al modello del 2023 per valutare le variazioni geomorfologiche avvenute sulla scogliera.

In sintesi in tale studio viene presentata la qualità delle ricostruzioni generate a partire dai tre dataset disponibili e vengono valutate due diverse tecniche di co–registrazione di dati fotogrammetrici multitemporali (approccio manuale *"point-based*" e automatizzato *"SIFT-based"*). Inoltre, grazie a un'attenta ricerca bibliografica e fonti giornalistiche (sia storiche che recenti) sono stati individuati e descritti i principali fenomeni di crollo che hanno interessato il sito di studio.

I risultati presentati indirizzano gli autori verso i prossimi step da seguire al fine di valutare e migliorare tale approccio per il monitoraggio costiero.

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ABSTRACT

Coastal cliff erosion is a significant hazard for the safety of people, buildings, utilities and infrastructure, given the sudden and episodic nature of the retreat process in time and space. Thus, understanding past retreat trends and a regular diagnosis of the cliff face condition is fundamental for risk management. In this study we show preliminary results of a project aimed at the definition of the coastal erosion (in terms of temporal and spatial scales) of a small portion of cliff located along the Maronti beach in Ischia, Italy. Drone-based and terrestrial acquisition approaches offered the opportunity to exploit photogrammetric techniques to estimate the spatial and temporal rate of change of the investigated portion of cliff.

In this study, cliff face topographical evolution is evaluated out by comparing the results obtained from three photographic datasets (variable approach either boat and UAV-based) obtained in 2011, 2021 and 2023. Spatial distribution of two main instability events dated back to 2020 and 2022 were well represented in the maps of change generated with the M3C2 algorithm. The comparison of point clouds for the period 2011-2021 and 2021-2023 produced max retreat rate of the cliff face of approximately 12 and 25 m, respectively.

Results highlighted the need for robust co-registration methods to accurately estimate erosion rates. Critical issues are discussed to highlight potentials and limitations encountered with the above-mentioned multi-temporal cliff evolution assessment techniques.

Keywords: Photogrammetry, drone, multi-temporal change, cliff, rockfall, 3D model, Maronti bay, Ischia Island.

INTRODUCTION

Past research reveals that instability occurrences of natural and engineered slopes are influenced by a range of factors including extensive human activities (Sidle *et alii*, 2004), improper land use (e.g. unauthorised construction works within marginally stable slope) (Parisi & Sabella, 2017; Luo *et alii*, 2019) and climate and its variations (Gariano & Guzzetti, 2016). Coastal areas are naturally dynamic and subject to critical variation over time due to a range of preparatory and triggering factors. In particular, sea cliff environments are often prone to several erosional processes able to constantly shape the coastal landscape. Natural phenomenon coupled with human-induced effects has significant consequences on sub-vertical coastal environments. Sunamura (1992), reports that problems of average cliff recession rates in excess of 1 m/year are experienced at coastal sites in Denmark, Germany, Russia, Japan, New Zealand, Canada, the UK and the USA.

Quantifying volumes and revealing patterns of cliff edge and face evolution, can provide critical information to understand the processes triggering cliff failures. Traditional field surveys for in situ direct measurements in sub-vertical coastal contexts are challenging for the operators and requires time-consuming efforts to capture numerous data to ensure spatial representativity. In the last decades, remote sensing techniques have proved to be efficient methods to analyse change along coastal area over time (Parente *et alii*, 2015; Apostolopoulos & Nikolakopoulos, 2021). The use of long-range remote sensing techniques (*e.g.*, satellite data, airborne SAR interferometry and airborne laser ranging) can be adopted to successfully provide large-scale monitoring such as the estimation of annual retreat rate of long stretches of coastline (Sun *et alii*, 2023). For the assessment of the activity patterns of a specific cliff sector the adoption of close-range solutions is a more suitable solution (Lim *et alii*, 2005). Such techniques including TLS and photogrammetry have proved their potential to understand and quantify evolution of the entire cliff section (Young *et alii,* 2010; Letortu *et alii*, 2018; Parente *et alii*, 2019).

For highly dynamics environments such as coastal cliffs, increasing the frequency of surveys can facilitate the estimation of change. Also, monitoring cliff change over a range of spatial and temporal scales requires utilizing a suite of historical and modern data. However, datasets for poorly studied cliff sections are often unavailable. A solution may be considering photogrammetry coupled to crowd-sourced photos and videos captured by amateurs (*e.g*., Alsadik, 2020; Rihani, 2023). The availability of photos for touristic sites is a considerable resource for research purposes although such photographic material often lacks accurate location information and can vary in quality depending on the acquisition sensors and platform used (e.g., smartphones, digital cameras, drones, etc.). However, the use of low-cost sensors such as smartphones can successfully perform valid SfM-based ('Structure from Motion') photogrammetric restitutions (Micheletti *et alii*, 2014; Jaud *et alii*, 2019). SfM-photogrammetry allows to generate 3D models (such as point clouds) that can be used to quantify topographic and volumetric changes over time to better understand multi-temporal geomorphic variations in a range of environments including seacliff (Yu *et alii*, 2022). Furthermore, manual and automated pipeline available in modern photogrammetric software can be adopted to automatically generate aligned multitemporal 2D and 3D models (Turner *et alii*, 2015; Feurer &Vinatier, 2018; Cucchiaro *et alii*, 2020; Parente *et alii*, 2021).

The site considered for this study is a portion of cliff situated along the Maronti cliff on the Ischia Island (Italy). Information regarding erosional events at Maronti cliffs are limited. To the best of the authors knowledge the only scientific work at Maronti consists in the estimation of the bay erosion modelling considering the sediment transport dynamics (Giordano *et alii*, 2006). Scientific information regarding the multitemporal morphological evolution of the cliff is not available. The purpose

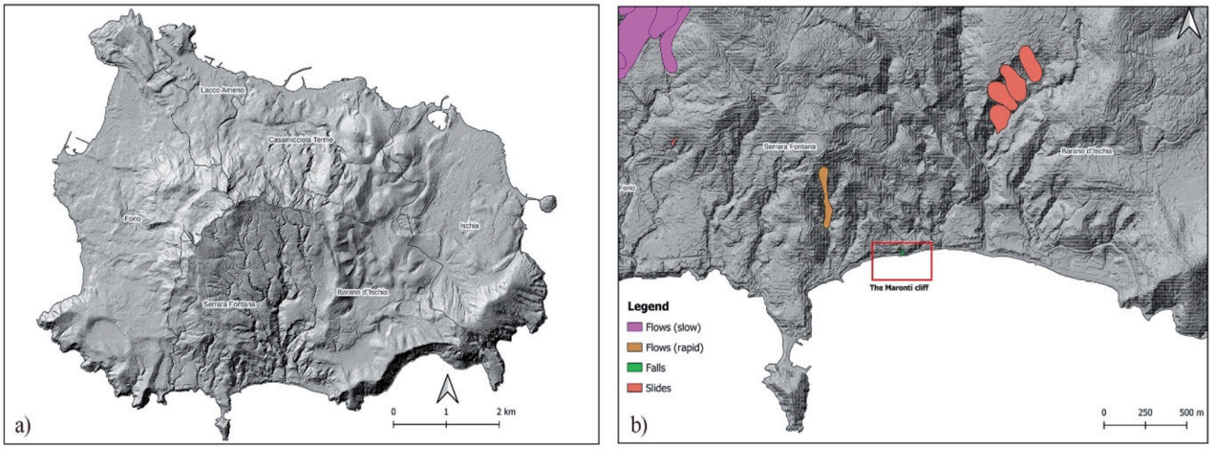

Fig. 1 - (a) The Ischia Island and (b) a zoomed view of the Maronti bay (study site in the red rectangle). Landslides affecting the area are depicted also as reported on the IFFI Project (Italian Landslide Inventory) from TRIGILA *et alii (2010)*

of the present work is to use multitemporal and multiperspective photographic datasets acquired from both, amateurs (crowd-sourced photos - GUERIN *et alii*, 2020) and experienced operators (topographic survey), to estimate preliminary data about the evolution of a highly unstable portion of the Maronti cliff. Furthermore, the work evaluated the ability of two different 3D models co-registration procedures to quantify the erosion rate and discuss opportunities for future work.

STUDY AREA

Ischia Island (Figure 1a) is located in the Gulf of Naples (eastern Tyrrhenian Sea margin, Italy), with an area of 46.3 Km^2 and is dominated by the Monte Epomeo (787 m a.s.l.), in its central portion and by the NE-SW Monte Vezzi - Monte Cotto alignment of peaks, in the SE corner. The investigated site is situated along the Maronti bay (Figure 1b), a two kilometres long pocket beach extending between two small peninsulas namely Sant'Angelo and Capo Grosso (from west to east). The study site is a small portion of cliff located in the central part of the Maronti bay affected by evident recent erosional processes including rock falls and rock topples (Figure 1b).

GEOMORPHOLOGICAL SETTINGS

The island represents the merged portion of a large volcanic field, covering at least 300 Km^2 in which eruptive mouths, calderic structures and resurgent structures have developed (ISPRA, 2009). It lies at the end of the continental shelf that delimits the northern and the central sectors of the Apennine chain. From north to east, the platform is connected to the coastline and connects Ischia, Procida and the Phlegraean volcanic district. To the northwest it descends toward the Gulf of Gaeta basin while to the south it deepens toward the deep basin of the Tyrrhenian Sea (VEZZOLI, 1988).

The analysis of historical sources and the results of archaeological studies not only reveal the fragility of the area, but also show that recent geological development, characterised by eruptions, earthquakes and landslides, has influenced the distribution of human settlements (GUADAGNO *et alii*, 1995)

From a geological point of view, the island is mainly composed of volcanic rocks and landslide deposits and subordinately of sedimentary terrigenous rocks, whose presence is to be linked to the alternating between complex eruptive phases and slope instability (DE VITA *et alii*, 2006, 2010; DELLA SETA *et alii*, 2012). From the oldest to the youngest, the main geological units are represented by the Ancient Ischia, by the San Nicola synthem, by the Buceto synthem.

The coastline of the Ischia Island has undergone significant changes in the past due to the important volcanic and tectonic evolution which have been associated phenomena of slope instability that have caused the retreat of the coastline on the order of hundreds of meters (DEL PRETE & MELE, 1999).

From a geological point of view the investigated site is characterised by the presence of the Maronti Formation. Over the last years this coastal sector has experienced multiple natural and anthropogenic events that have shaped the general morphology and bathymetry of the area (*e.g.*, extreme storms, nourishments, cliff cuts, installation of mitigation measures, etc.).

National newspapers have reported on the various events that have affected the cliff since 1970 (POPOLI *et alii*, 1978). In particular, the studied cliff portion appears to have undergone multiple phenomena affecting its stability. The first evidence of instability was reported on 7^{th} June 1978, which caused the death of five people and three injured.

Newspaper reports that the 20-meter-high cliff suddenly collapsed shortly after 12 noon (Figure 2).

Another significant event is the one in August 1983, again documented by National newspaper when several hundred cubic meters of debris rock collapsed, permanently burying a factory that had already been closed due to previously occurring phenomena.

Fig. 2 - The Maronti landslide, June 8, 1978 (extracted from: "Il Mattino")

Recently, two main instability events occurred on December 15, 2020, and November 22, 2022. The 2020 event caused the edge of the cliff to approach the road and homes in the immediate vicinity while the 2022 collapse completely destroyed a long stretch of the road and seriously damaged neighbouring properties. The current condition of this portion of the cliff is well represented in Figure 4.

MATERIALS AND METHODS

Datasets

The set of photos used in this study were collected in 2011, 2021 and 2023 from a range of different sensors and for different purposes. A detailed description of the used datasets is reported in Table 1.

Year	September 2011	July 2021	May 2023
Acquisition platform	DSLR	Smartphone	Drone
Camera	Nikon Coolpix P100	Huawei FIG-LX1	Autel Evo 2 Pro
Number of phots	11	12	92
MP	10.3	8	
Distance from the object	Range: ~50-100m	Range: ~50-150m	Range: ~40-100m
Purpose of acquisition	Tourism	Tourism	Monitoring and inspection
Topographic surveys	-	-	GNSS station (6 GCPs)
Weather conditions	Sunny	Sunny	Sunny

Tab. 1 - Details about the acquisition of each photographic dataset

Summarising, sets of photos acquired on 17th September 2011 and 20th July 2021 were collected from a boat at a range of distances and from different angles of view. A total of 11 and 15 photos formed the 2011 and 2021 datasets, respectively. Although the previous set of photos were not intended for photogrammetric processing, the acquisition geometry, spatial coverage and quality of images were suitable for the photogrammetric Structure-from-Motion workflow adopted in this study.

The drone-based survey was carried out on 23rd May 2023 with the Autel Evo 2 Pro Enterprise RTK equipped with a RGB camera (note: the drone was not equipped with the RTK module at the time of acquisition). The drone-based data collection was conducted manually by an expert operator that captured a total of 92 images of the site from a range of perspectives flying approximately from 40 to 100 m from the centre of the investigated cliff. Flight height and distance from the cliff were not constant during the acquisition, thus a GSD (Ground Sample Distance) value cannot be estimated.

Image acquisition geometry of each dataset was reconstructed as part of the SfM camera alignment process and is reported in Figure 3.

A further dataset collected before flying the drone, includes the position of six photogrammetric targets well distributed on the study site (Figure 4). The targets were used as ground points to ensure the correct georeferencing of the photogrammetric outputs. The position of their centres was estimated using the GNSS positioning technique (Figure 4).

A South Galaxy G7 GNSS receiver allowed determining the spatial position of a total of 6 targets using the RTK (Real Time Kinematic) method, with an accuracy of up to 2 cm, depending on the number of visible satellites, GSM signal and corrections from a base (Topcon NETG3 receiver) located on Ischia Island (municipality of Barano d'Ischia) a few km away from the study site.

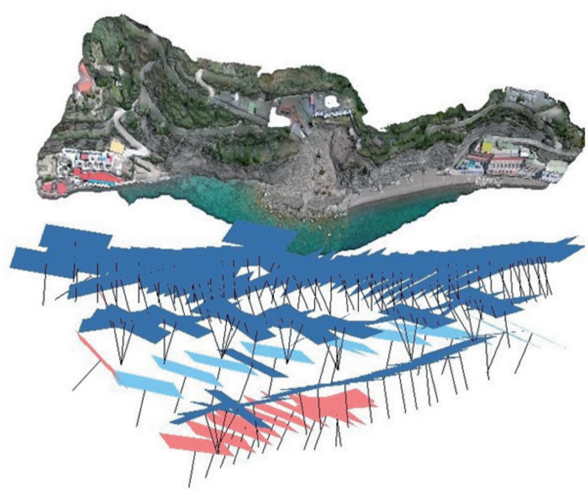

Fig. 3 - Photo acquisition geometry – Camera legend: Dark blue – 2023; Pink – 2021; Light blue – 2011

Processing and 3D models coregistration

The imagery captured at the sea-cliff site was processed using a classic SfM-MVS pipeline. The SfM-MVS photogrammetric processing was implemented entirely in Agisoft Metashape v.1.7.4 (AgisoftMetashape, 2023).

Fig. 4 - Photogrammetric targets locations (above) and example of targets measurement (point 2 – bottom right; point 6 – bottom left)

For each set of images, a five-step procedure was used to generate a dense point cloud. These steps included: loading the four images into the software; estimating camera pose and photos orientation via the 'SmartMatch' tool; georeferencing the sparse point cloud in a global coordinates system using the photogrammetric targets coordinates previously measured with a GNSS receiver (only possible with the 2023 dataset); optimizing the model and minimizing the error in all marked points, 3D points and camera station positions and angles; and increasing the point cloud density via the MVS algorithms and rendering the model with RGB values. All processing parameters were kept constant for the generation of each 3D model. The absence of photogrammetric targets on the imagery collected in 2011 and 2021 lead to the generation of dense point clouds in an arbitrary coordinate system. Also, the models were not correctly scaled. Therefore, in order to conduct a proper multitemporal cloud-to-cloud analysis, it is necessary to adopt a solution for transforming all 3D models and 2021 as 'compared' ones. The purpose of this registration is to estimate a 3D similarity transformation between the reference and the compared models. This was achieved by the manual selection of well- distributed correspondent points (also indicated as point-pairs) between the reference model and the compared one. When using this solution, it is normal practice to identify natural and/or anthropological features considered stable over the monitoring period (Bakker & Lane, 2017).

The second registration procedure followed instructions furnished in Parente *et alii* (2021) for the so-called Time-SIFT solution. This procedure allowed to co-register multitemporal SfM-MVS-based models through the identification of tie-points over multitemporal images. An advantage of the above-mentioned approach is the ability to co-register 3D models even when using multisource and multi-perspective data, captured across widely varying spatial and temporal scales.

Multi-temporal analysis

After aligning the multitemporal 3D datasets, analysis of change was conducted using the multiscale model-to-model cloud comparison (M3C2) plugin (Lague *et alii*, 2013). The M3C2 is a sophisticated cloud-to-cloud comparison method implemented in CloudCompare (2023) which computes signed distances along surface normals. It does not imply the interpolation of surfaces and it is particularly advantageous for applications on complex 3D objects typical of landscape environments. This approach has been employed for many studies investigating geomorphic change (Cook & Dietze, 2019; Di Francesco *et alii*, 2020; Mazza *et alii*, 2023).

The M3C2 algorithm is a two-step pipeline which compares point to point cloud data using surface normals that are consistent with surface roughness and measure the change that occurs along the normal direction.

This approach provides more reliable accuracy estimates when compared to other comparison approaches as it accounts for sources of uncertainty due to surface roughness and models registration (Stumpf *et alii*, 2015).

Considering the surface roughness of the site of interest, the M3C2 plugin waspreferred for the comparison between multi-temporal point clouds. The parameters for the above algorithm were set based on suggestions found in Lague *et alii* (2013) and are stated in Table 2.

Normals (D) (m)	Projection (d) (m)	Max depth (m)	Registration Error (m)	Core points	Normals (calculation mode)	Preferred orientation
0.5	0.3	10-25	0.5	Could #1	Default	-Y

Tab. 2 - M3C2 parameters used for this study

For this study analysis of change on the cliff face was carried out for the following multitemporal comparisons: 2011-2021 and 2021-2023. This allowed to characterise the two main rockfall events occurred in December 15, 2020 and November 22, 2022. Both co-registration procedures were used, allowing to generate a total of four maps of change. Note that the same M3C2 parameters were used for all 3D comparisons.

RESULTS

A total of three 3D point clouds were generated through the photogrammetric processing of the 2011, 2021 and 2023 datasets. Figure 5 allows to evaluate the reconstruction completeness for each point cloud. As expected, point cloud density is different for each reconstruction. Specifically, the 2011 and 2021 3D models, are characterised by lower quality in terms of spatial coverage when compared to the 2023 counterpart. Interestingly the 2011 dataset produced a 3D reconstruction with a much higher number of points compared to the 2021 set of photos. Missing points in 2011 and 2021 3D models are not preventing comparisons with the 2023 model and the generation of change of maps through the M3C2 plugin.

Considering the alignment achieved with the two co-registration approaches (point-pairs and SIFT) evident differences are observable (Figure 6). Considering the high erodibility of the cliff, Figure 6(a, c) depicts a more reasonable alignment for the point-pairs co-registration where the older reconstruction dated back to 2011 (point cloud coloured in red in Figure 6a, c) is positioned ahead the other reconstructed models on most of the investigated cliff. However, an abnormal behaviour is observed on the right side of the reconstructions where the 2023 point cloud stands above the other two. This is observed in Figure 6 (b, d) for the SIFT registration also. The SIFT registration appears to be less accurate with most of the 2023 reconstruction covering the other

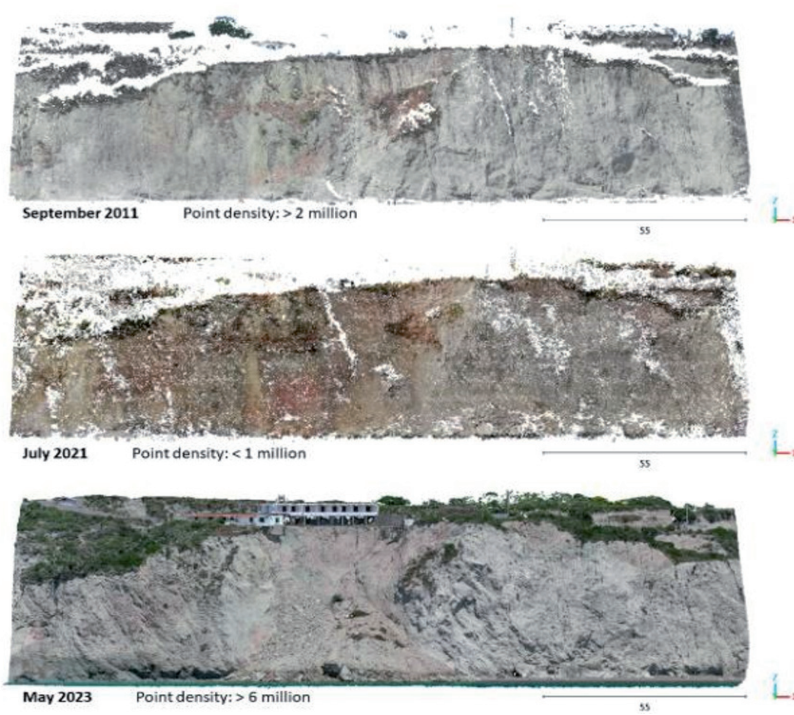

Fig. 5 - An overview of the point clouds reconstruction quality

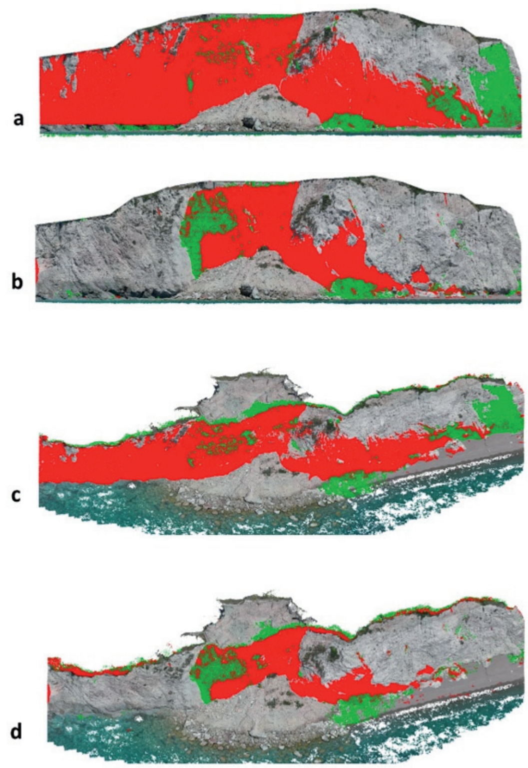

Fig. 6 - Point clouds alignment differences between the two co-registration approaches. Differences are shown in two perspectives: frontal view: (a) point-pairs and and (b) SIFT; top-oblique: (c) point-pairs and (d) SIFT. Point cloud legend: red (2011)

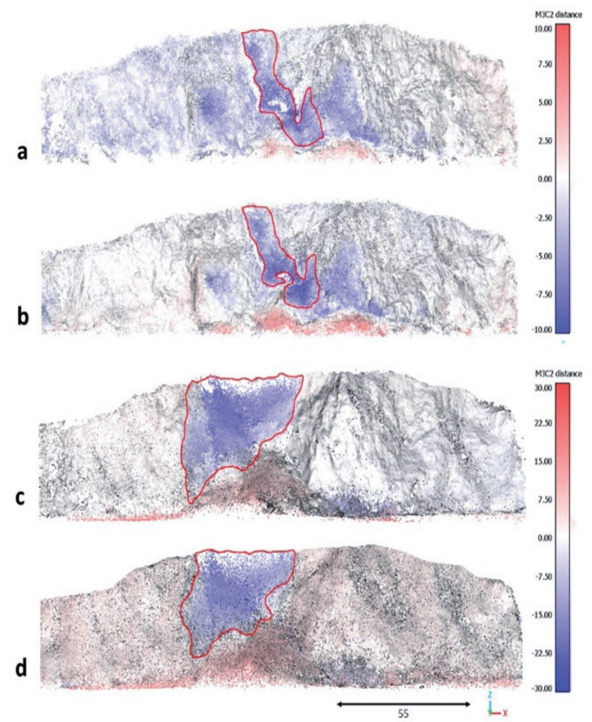

Fig. 7 - M3C2 maps of change obtained for a range of comparisons combinations: (a) 2011-2021 point-pairs; (b) 2011-2021 SIFT; (c) 2021-2023 point-pairs; and (d) 2021-2023 SIFT. The red polygon shows the area considered for the average retreat rate and volumetric estimation

two point clouds. Such alignment differences tend inevitably to affect the accuracy of the multitemporal change analysis.

The map of change for the 2011-2021 shows differences of max +10m and min -10m. The period 2021-2023 that includes a larger rockfall event depicts variations of the cliff face in the range +30 m and -30 m. Observing the spatial distribution of change illustrated in Figure 7(a, b) it is evident that the point-pairs and SIFT registration produces comparable results with erosive events well defined in the centre portion of the cliff (in blue) and area of accumulation at the bottom (in red). The left side of the studied cliff in the change of map of Figure 7a produced well distributed negative values that indicates probable minor erosional events.

A distinct pattern of erosion characterise Figure 7(c,d) where the main collapse of the cliff dated back to December 15, 2020 and November 22, 2022 is well represented. For the period 2021-2023 the main potential erroneous data in terms of estimated changes are observable in Figure 7d (SIFT alignment) where the presence of area of accretion (in reddish)

on the left and right side of the cliff indicates potential misalignment. The previous observation is valid for the point-pairs registration only on the left side of the cliff.

Approximate ranges of retreat values estimated for the central portion of the cliff indicated with the red polygons in Figure 7 (sectors affected by the major instability events) are as follows: for the period 2011-2023: 7-12 m (point-pairs) and 5.5-11.5 m (SIFT); for the period 2021-2023: 5-25 m (point-pairs) and 3-24.5 m (SIFT). Furthermore, preliminary analysis carried out with the “2.5 Volume” tool in CloudCompare allowed to define the material loss for the two investigated periods. Following results in terms of removed material were estimated: ≈ 7500 m^3 (2011-2021) and ≈ 14000 m^3 (2021-2023).

DISCUSSION AND CONCLUSION

The availability of state-of-the-art software allows for the generation of high-accuracy and high-resolution results even when using images acquired with low-cost sensors and also to use algorithms to automatically register multitemporal datasets (Feurer & Vinatier, 2018; Jaud *et alii*, 2019).

The 2011 and 2021 sets of photos used in this study were captured by amateur operators with a good overlap percentage even if a rigorous acquisition geometry was not carried out. This allowed for the adoption of a SfM-MVS photogrammetric workflow and the generation of dense point clouds. The 2011 datasets allowed for the generation of a much denser point cloud when compared to the 2021 counterpart. Considering the similar number of photos processed for both datasets and same weather conditions, this result was probably influenced by the better quality of the DSLR camera sensor and the lower acquisition distance (increased average GSD) of the 2011 dataset.

As expected, point cloud reconstruction for 2011 and 2021 present noticeable differences when compared to the 2023 model. According to Jaud *et alii* (2019) a number of factors can cause such differences including camera geometry during acquisition, number of photos processed and effectiveness of tiepoints detection that is influenced by GSD value, photo overlapping and variation in site illumination. The effectiveness in tiepoints detection is critical not only for the generation of accurate results but also for the adoption of automatic co-registration procedures (Parente *et alii*, 2021).

Results of change detection of this study are unavoidably affected by multiple sources of errors. Many aspects may influence the quality of a 3D reconstruction including camera system selection, calibration, network configuration, acquisition procedure and survey scale (Mosbrucker *et alii*, 2017), software used (Niederheiser *et alii*, 2016) and external factors (*e.g.*, site characteristics, weather and light conditions, etc.).

A quantitative accuracy assessment between point clouds obtained with amateurs set of photos (2011 and 2021) and the drone-based dataset (2023) was not possible. Estimation of the root mean square error (RMSE) between the multitemporal constructed 3D results requires the definition of unchanged features (*e.g.*, Yu *et alii*, 2022). However, identifying multiple stable points is complex and highly subjective considering the dynamicity of the study site and the lower coverage and spatial resolution of the reconstructions obtained for 2011 and 2021. Similarly, a quantitative assessment to evaluate the two co-registration approaches proved to be difficult for the same reasons. Future work will be addressed to define proper evaluation of the above quantitative assessment.

As shown in Figure 6 an initial qualitative assessment was conducted to preliminary define the co-registration approaches. From the graphical result it is clear that the two approaches present significant differences that are reflected on the maps of change generated (Figure 7). This highlights the need to conduct further scientific observations to accurately define difference values between the two co-registration approaches.

Adoption of an Iterative Closest Point (ICP) algorithm can provide an improvement in terms of alignment of portions of point clouds. This approach minimises the square errors between correspondences when a reasonable alignment is already estimated between the two multitemporal datasets. However, this approach was not adopted because of the already mentioned difficulty in identifying and removing the active zones which have potentially changed between surveys. In fact, isolating areas of the 3D model where change may have occurred is critical to maximise the quality of the ICP registration and obtain reliable ICP transformation parameters (Turner *et alii*, 2015).

Although results shown in this research need further analysis, this is the first study investigating the instability events along a portion of the Maronti cliff that has caused significant recession and critical loss of infrastructure over the last years. It is recognised the need to carry out a robust workflow to estimate uncertainties inherent in data co-registration and subsequent topographic and volumetric change analysis. Furthermore, testing further co-registration methods (Cucchiaro *et alii*, 2020) and volumetric calculation methods (Štroner *et alii*, 2019) can refine results. The previously described work will be integrated with further research approaches including the use of satellite data. Quantifying volumes and revealing patterns of cliff edge and face evolution, will provide critical information to understand the processes triggering cliff failures at Maronti bay. Also, using satellite-based analysis can reveal essential information to understand the influence of development and engineering structures on coastal erosional patterns (*e.g.*, Parente *et alii*, 2015).

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