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LANDSLIDE IMPACT ON NATURE RESERVES: FIRST RESULTS ON THE MULTISENSOR SURVEY OF UNSTABLE SLOPES IN PROTECTED AREAS

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EXTENDED ABSTRACT

I parchi e le riserve naturali rappresentano aree tutelate che ospitano ecosistemi naturalisticamente rilevanti per diversità e/o conservazione delle risorse. In tutto il mondo questi sono considerati siti di straordinaria bellezza naturale e patrimonio culturale, fungendo quindi anche da meta turistica. Questo aspetto pone, però, l'attenzione sulla fruizione in sicurezza di queste aree naturali, che sono spesso sede di rischi ambientali. Le frane, ad esempio, possono essere annoverate tra le più frequenti minacce per la fruizione di parchi e riserve naturali, in quanto rappresentano fenomeni che talora coinvolgono ingenti volumi di terre e rocce con un elevato potere distruttivo. Al fine di una corretta gestione del rischio, specialmente in termini di prevenzione, bisogna sempre partire dallo studio di questi fenomeni, sia pregressi che potenziali, quindi dalla caratterizzazione morfologica e geologico-tecnica dei luoghi. Tuttavia, le rigide regole imposte all'interno delle aree protette spesso rappresentano una limitazione allo svolgimento di estesi rilievi di carattere tecnico che prevedono un grado di disturbo ambientale. È quindi necessario operare con tecnologie che garantiscano il minimo livello di invasività ma che, allo stesso tempo, consentano il valido rilievo di dati di campo al fine di pervenire a modelli della franosità affidabili, anche per finalità di monitoraggio. Questo studio riguarda l'impiego di tecniche di rilievo digitale di prossimità per l'identificazione e la mappatura di fenomeni franosi lungo versanti situati in aree protette, nell'ambito di un più ampio progetto di ricerca finalizzato all'analisi digitale di modelli di versante. Le tecniche qui messe a confronto riguardano applicazioni fotografiche e fotogrammetriche, sia da terra che da drone, e l'utilizzo di termografia ad infrarossi in due aree campione. Nel primo caso studio, l'analisi riguarda alcune falesie rocciose presenti lungo la costa del Parco Nazionale delle Cinque Terre (Liguria orientale), costituite da ammassi rocciosi di natura flyschoide appartenenti all'Appennino settentrionale.

Qui i meccanismi di instabilità sono correlati a molteplici sistemi di discontinuità derivanti dal complesso assetto geometrico e strutturale degli ammassi rocciosi. L'analisi di fotografie aeree oblique ha consentito, mediante fotointerpretazione, di rilevare gli indicatori geomorfologici di movimenti franosi passati e di effettuare osservazioni preliminari sugli affioramenti instabili più rappresentativi da indagare mediante metodi di telerilevamento in studi di approfondimento futuri. Il secondo caso studio è incentrato sull'analisi digitale di una parte della scarpata rocciosa delle Timpe di Acireale (Sicilia orientale), che rappresenta una falesia costiera di origine tettonica che espone in affioramento terreni di natura vulcanica. L'impiego di sensori digitali di prossimità per il rilievo aerofotogrammetrico ha consentito la realizzazione di una nuvola di punti da sfruttare per finalità di riconoscimento e mappatura di frane pregresse. La stessa falesia è stata oggetto di rilievi di termografia ad infrarossi, eseguiti sia da imbarcazione sia da drone, che hanno consentito di riscontrare i segni della franosità fornendo la possibilità di validare il dato fotogrammetrico.

In entrambi i siti di studio è stato garantito un livello di disturbo ambientale pressoché nullo, e sono state messe in luce sia le potenzialità sia le limitazioni delle tecniche utilizzate per finalità di rilievo geomorfologico della franosità in aree protette. I risultati ottenuti, ancorché preliminari, rappresentano un solido punto di partenza per il monitoraggio multisensore delle aree di interesse finalizzato non solo alla definizione di modelli di franosità, ma anche alla valutazione della suscettibilità dinamica da frana.

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ABSTRACT

This study is focused on the use of digital close-range remote surveying techniques for the identification and mapping of landslide phenomena along rock slopes in protected areas. This activity is part of a research project aimed at the digital analysis of slope models. The techniques compared herein are based on photographic and photogrammetric applications, carried out from both ground and aerial surveys, and on the use of infrared thermography in two test sites located within the Cinque Terre National Park (Liguria, Italy) and the "Timpa di Acireale" nature reserve (Sicily, Italy). The analysis of oblique aerial photographs allowed detecting key geomorphological indicators of past landslide movements and to carry out preliminary observations on unstable outcrops. The use of digital close-range sensors for the aerial photogrammetric survey allowed building a digital slope model to be analysed for the recognition and mapping of previous landslides. Moreover, key structural features, likely controlling the slope stability, were highlighted. Infrared thermography allowed detecting signs of landslides, providing the possibility of validating the photogrammetric data. In both protected areas, an almost zero level of environmental disturbance was guaranteed. Finally, both the potential and limitations of the techniques, used for the non-invasive morphological survey, are highlighted.

Keywords: *landslide, photogrammetry, infrared thermography, non-destructive survey, close-range remote survey.*

INTRODUCTION

Parks and nature reserves represent areas set aside with the purpose of preserving and protecting relevant ecosystems and/or outstanding natural, cultural, and historical heritages. Tourism activities play a key role in enhancing and communicating to future generation both value and beauty of these sites. However, many protected areas and heritages are threatened by the impact of natural geo-hazards (*e.g.*, landslides, earthquakes, volcanoes, sea storms), giving rise to risk scenarios (Valagussa *et alii*, 2021). Landslides are among the most frequent natural hazards impacting these fragile heritages (Pappalardo & Mineo, 2015; Pepe *et alii*, 2020; Pappalardo *et alii*, 2021). Indeed, the occurrence of landslides can pose a risk to the fruition of nature reserves and parks since it can affect the safety of visitors and workers, as well as the functionality of structures and facilities (Raso *et alii*, 2019; Mineo *et alii*, 2021). Therefore, the investigation on slope stability is of paramount importance to schedule effective risk mitigation strategies aimed at achieving a safe fruition of protected sites, as well as their proper management and conservation. However, in protected areas the analysis of landslide dynamics may not be an easy task, especially in case of unstable rock slopes. Sometimes, the execution of field surveys can be limited by specific protection regulations. Moreover, when dealing with high, steep and wide rocky walls, the direct survey of rock masses is often hampered by logistic and economic constraints (*e.g.*, scarce accessibility, low spatial representativeness of data, rugged topography). Considering this, the exploitation of multi-sensor remote sensing data can be undoubtedly useful in assessing rock slope stability. In this context, remotely sensed data can be acquired by means of a wide range of non-invasive and cost-effective techniques, making them ideal to be used within parks, reserves, and other protected areas, thanks to their low to null impact on the natural environment, as well as in case of inaccessible slope sectors (Riquelme *et alii*, 2016). In this regard, many authors showed that non-contact geo-structural and geo-mechanical characterization of rock masses can be helpful in detecting and assessing rock failure susceptibility (De Vita *et alii*, 2012; Casagli *et alii*, 2017; Mineo *et alii*, 2024). Nevertheless, in this field of research the advantages and perspectives on the use of remote multi-sensor approaches are currently under full exploration.

A further contribution to the use of remote multi-sensor data sources for landslide characterization is described in this work with reference to slope instabilities involving coastal slopes. Specifically, the preliminary results of the activities carried out in the frame of an Italian PRIN project (National Interest Research Projects) are presented. The recognition of landslides and related morphological features were carried out through *i*) oblique aerial photographs interpretation and *ii*) aerial photogrammetry by Unmanned Aerial Vehicles (UAV), even coupled with InfraRed Thermography (IRT). Two representative sites were selected in the Italian regions of Liguria and Sicily, within the Cinque Terre National Park and the "Timpa di Acireale" nature reserve, respectively. The gathered insights into the main morphological elements linked to previous and potential slope instabilities represent an essential background for slope failure susceptibility assessment. Furthermore, the preparatory surveys provided important clues for understanding both the potential and limitations of the techniques used for the non-contact surveys in the two pilot areas.

THE STUDY AREAS

For this research project, two highly renowned Italian nature reserves have been chosen as test sites. The first one is located in eastern Liguria Region (La Spezia Province, NW Italy) along a rocky coastal stretch of the Cinque Terre located just east of Vernazza (Figure 1a). Owing to the outstanding environmental, cultural and historical significance of its coastal terraced landscape, the Cinque Terre area is included in the list of UNESCO World Heritage Sites since 1997, whereas in 1999 it was declared National Park (Brandolini, 2017; Raso *et alii*, 2021). The selected site consists of an active sea cliff enclosing a small bay limited to the west by a pronounced headland, on the top of which part of the Vernazza hamlet stands; the eastern border coincides with the terminal part of a small ridge reaching the sea. Cliffs are cut in flysch sequences dominated by thinly bedded fine-grained sandstones and siltstones of the Macigno Formation, which belongs to the Tuscan Nappe of the Northern Apennine. During the orogenic phases, these sedimentary bodies were deformed by a wide overturned southwest verging antiform fold, and subsequently were displaced by systems of normal faults correlated to the Plio-Quaternary tectonic evolution of the Ligurian Sea. Due to the interplay between geo-structural and geometrical features of the sets of discontinuities affecting sedimentary rock masses, several rock instability mechanisms were documented in the past (Cevasco, 2007). Since the area immediately above the cliff edge is crossed by the most travelled path by hikers (*i.e.*, trail number 592, also known as Verde-Azzurro trail), while the small beach at its toe can be frequented by bathers, inevitably potential risk scenarios occur (Raso *et alii*, 2019, 2021).

The second area stands along the eastern coastline of Sicily, in the municipal area of Acireale town, known as "Timpa di Acireale" (TdA) (Figure 1b). It is a natural escarpment of tectonic origin, whose existence is linked to the displacement of one of the major faults crossing the Ionian Sea. According to some authors, in fact, this would represent the northern termination of Malta Escarpment, a significant system of deep faults that extends from the study area as far as the island of Malta (Scandone *et alii*, 1981). Thanks to the "enormous naturalistic, geological and landscape heritage" the oriented nature reserve TdA was established in 1999 entrusted to the management of the Regional Department of State Forests to preserve and enhance its territory, where it is possible to find a wonderful natural heritage, with panoramic landscapes and enchanting places. From the lithological point of view, the escarpment exposes a volcanic succession represented by the alternation of massive lava banks and scoriaceous portions with the occurrence of continental clastic deposits (Corsaro *et alii*, 2002). This peculiar geological setting represents a weak feature of TdA escarpment, which suffers from a widespread slope instability. Indeed, numerous landslides occurred therein in historical times. Most of these are rockfall, debris-falls and complex landslides triggered by both rainfalls, seismic shakings, and aseismic creep movements (Barbano *et alii*, 2014).

METHODOLOGICAL APPROACH

The methodological approach followed for this study relies on the application of different close-range remote surveying techniques, which allowed the non-invasive morphological analysis of unstable slopes located within the restricted areas of chosen sites. The aim of this approach is to shed light on the potential and limitation of digital procedures, characterized by a variable complexity, when applied to such a specific case setting.

The surveying techniques taken into account herein are the digital oblique photo interpretation, the aerial photogrammetry and the infrared thermography (IRT). The first technique, applied to the study of the Vernazza site, is commonly employed to qualitatively reconstruct the geomorphological dynamic of coastal zones over time and to map the ground-effects of sea storms (Morgan & Krohn, 2014; Warrick *et alii*, 2017). In this study, oblique aerial photos freely available from the Liguria Region Geoportal have been used. Photographs were taken at oblique angles from a helicopter flying at an average elevation of 320 m during aerial surveys performed in 2015, and they are provided at 1:5,000 scale. The surveys have been performed by capturing the coastal area encompassing the nearshore up to the edge of sea cliffs or the top of coastal slopes, and sometimes including in the background the portions of the immediate hinterland. The geological and geomorphological interpretation of the gathered oblique photos have been performed to detect features directly and indirectly related to rock slope instabilities, such as edge of landslide scars, landslide deposits, clues of detached rock blocks. The discerned geological and

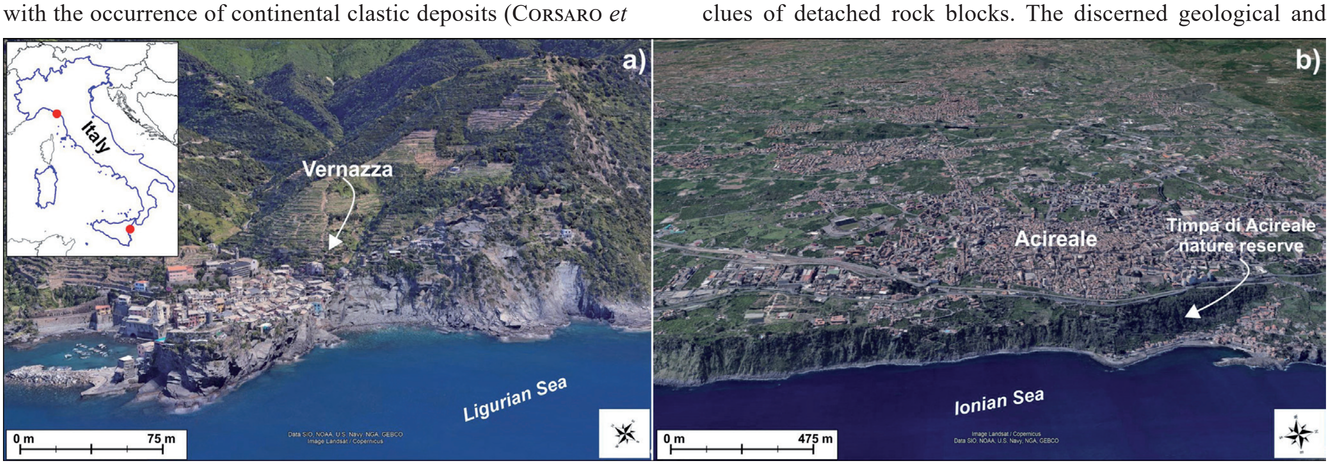

Fig. 1 - Location of test sites: a) costal cliffs at Cinque Terre National Park; b) Timpa di Acireale nature reserve (modified from Google Earth)

geomorphological elements have been graphically mapped on the oblique photographic view of the investigated rocky cliff.

In the TdA study site, the aerial photogrammetry by Unmanned Aerial Vehicle (UAV) was chosen to achieve a digital slope model of a sector falling along the Timpa escarpment. This technique relies on the acquisition of overlapping images, which enables the generation of 3D models from sequences of 2D images through the Structure from Motion technique (SfM) (Westoby *et alii*, 2012). This method involves capturing a series of overlapping photographs of a subject from various perspectives. Through these images, the SfM technique reconstructs the three-dimensional structure by identifying and correlating common points between the photographs (Eltner & Sofia, 2020). This is achieved through a sophisticated triangulation process in which SfM algorithms determine the three-dimensional coordinates of specific points within the scene. The algorithms analyze and interpret the variations and similarities in the images captured from multiple angles, allowing for the accurate construction of a detailed 3D representation of the framed object. This approach is essential for precisely capturing the complexity and nuances of the subject, offering a comprehensive and precise dimensional perspective. In the TdA area, the airborne survey was carried out by using an EVO Dual Enterprise V3, equipped with a high-resolution thermal imaging camera and a 50-megapixel Sony 0.8-inch CMOS sensor RYYB. A series of images of the cliff (camera optical axis trim between 0° and 45°) were taken ensuring a constant Ground Sample Distance and a 70-80% overlapping rate between adjacent photos. Nadiral flights (camera perpendicular to the ground surface) allowed a more accurate model reconstruction.

Along the TdA cliff, IRT images were also acquired both during the UAV flight, with a 640 × 512 high-resolution thermal imaging sensor featuring a 13mm focal length lens, and from a frontal perspective by using a 1024×768-pixel thermal camera. Surveys were carried out both under environmental daylight condition and in dark condition. The use of this technique to characterize landslide areas returned satisfactory outcomes when applied to both rockfalls and complex landslides (Fiorucci *et alii*, 2018; Frodella *et alii*, 2020; Caliò *et alii*, 2023; Vivaldi *et alii*, 2023). It is based on the surveying of the radiation emitted by a target of a known emissivity, which is directly proportional to its surface temperature, according to the Stefan-Boltzmann law. Acquired images were post-processed by the FLIR Research Studio tools, which allowed highlighting some key elements connected to the slope state and morphology.

RESULTS

The Vernazza case study

The examination of aerial oblique photographs allowed to qualitatively outline some relevant geological and geomorphological features of a stretch of rocky coast which extends for approximately 350 m (Fig. 2a). Towards Vernazza village, cliffs consist of vertical and sub-vertical rock walls which reach a maximum height of approximately 40 m along the sections located just below the mediaeval tower. This segment is actively affected by sea cliff retreatment dynamics since it is directly exposed to sea waves coming from the S and SE directions. For this reason, along some short stretches, small remnant of bedding surfaces with daylight exposure are visible from the oblique view. However, the bedding surfaces appear to outcrop with variable attitude, probably because sandstone and siltstones layers are involved in systems of parasitic folds at the meso-scale of observation. Moving laterally, at the cliff base, an ephemeral beach along with partly buried and damaged coastal engineering works (i.e., groynes) occur. This coastal deposit is mainly supplied by the solid discharge of the Vernazza stream, which was diverted through a short tunnel during the second half of the XIX century (Fig. 2b). Here, the cliff results from steep to very steep according to photointerpretation. By observing the rock wall, the visible bedding surfaces of rock layers appear to be oriented roughly parallel to the dip direction of the slope and intersected by other discontinuity systems with variable persistence. This condition suggests the presence of slope instabilities correlated to rock sliding mechanisms. This is confirmed by the observation of several traces of detached rock blocks (Fig. 2b). Eventually, just right of the small bay, the continuity of the sea cliff is interrupted by a wide rockslide deposit (Fig. 2c). The upper and middle portions of the accumulation are almost totally covered by shrubs, while the toe is currently eroded by wave action. In this portion, large tabular rock blocks can be seen (Fig. 2c). The landslide has been detached from the ridge of the coastal slope, where the main crown and the main scar are still visible, albeit partly vegetated. This sector is also cut by the path of the highly frequented Verde-Azzurro trail. Here, from the oblique aerial prospect, pieces of the bedding surface, where rock blocks slipped down, can be noticed.

The Timpa di Acireale case study

The photogrammetric survey allowed building a dense point cloud of 23,145,277 points. Oblique and frontal images were acquired from an averagely constant distance of 150 meters, while a slightly higher distance was set for nadir flights, approximately covering a 240,000 m² area. This resulted in an average ground sample distance (GSD) of about 5.5 cm/pixel. The built digital slope model refers to an about 450 m long TdA coastal sector (Fig. 3a), which can be analyzed from different perspectives to highlight three-dimensional morphological features linked to slope instability. From the morphological point of view, the surveyed TdA sector is a 75-80 m high scarp, characterized by a 70° mean slope angle. The slope upper face has an average inclination of about 20°, while at its foot there

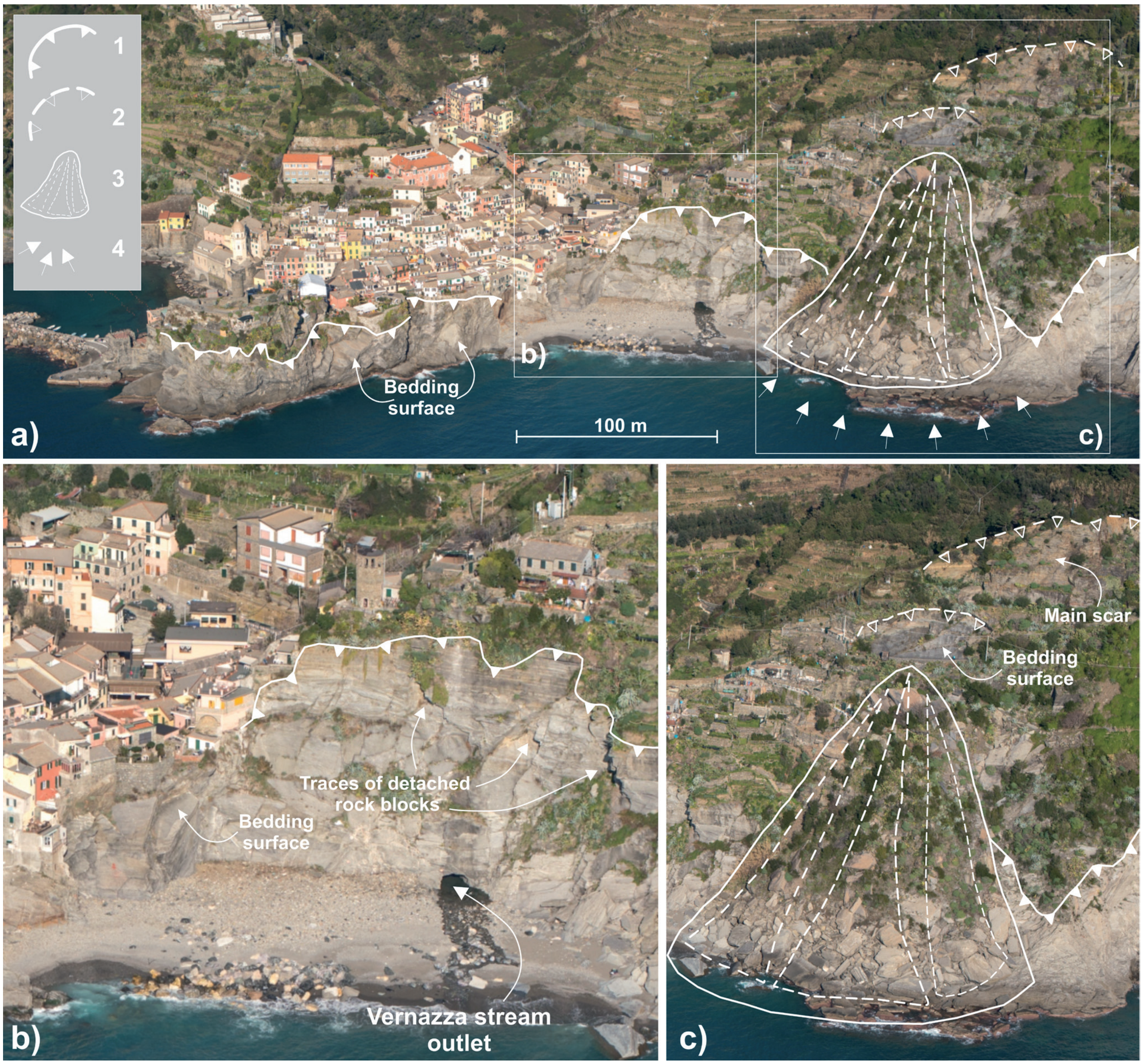

Fig. 2 - a) Panoramic view of the Vernazza pilot site from oblique photograph. b, c) details of two selected sectors of the rocky coastal stretch. LEGEND: 1) active sea cliff edge; 2) inactive landslide edge; 3) landslide deposit; 4) sea wave erosion

is an about 10 meters wide shoreline. Two focus areas, hosting different types of landslides, have been examined in detail herein (Fig. 3a). Z1 focus area is characterized by the presence of a deep scar along the vegetated slope, which shows distinctive features of a past landslide. It is, indeed, characterized by a wide zone of depletion (Fig. 3b), which is well visible from a frontal perspective. This zone is likely bordered by two distinct linear segments, suggesting a structurally controlled failure. This structural pattern seems to be defined by two major discontinuities intersecting to form a wedge (Fig. 3b-c). Their indicative orientation in space, measured on the georeferenced dense point cloud, is WNW-ESE (S1) and NE-SW (S2). Below the zone of depletion, a sort of bottleneck between two massive volcanic outcrops defines the path of the failed volume, which likely dig a channel in the rock masses. Underneath this feature, the landslide foot is still recognizable due to its topographic elevation than the surroundings. Its shape has been strongly modified over time by the wave action, although it can be still mapped from a high-angle perspective (Fig. 3c). The presence of vegetation within the zone of depletion, as well as the partial obliteration of the foot deposit, suggests that this landslide is not recent.

Z2 hosts signs of two mass movements, developing from the highest cliff sector (Fig. 3d). In this case, the landslide crowns are visible, but no evidence of deposit at the foot of the cliff is highlighted. Landslide 1 (L1 in Fig. 3d) is the most evident, probably due to its young age, and shows signs of recent activity right below the crown. It appears as a shallow movement, and it is highlighted by the absence of vegetation. On the other hand, Landslide 2 area

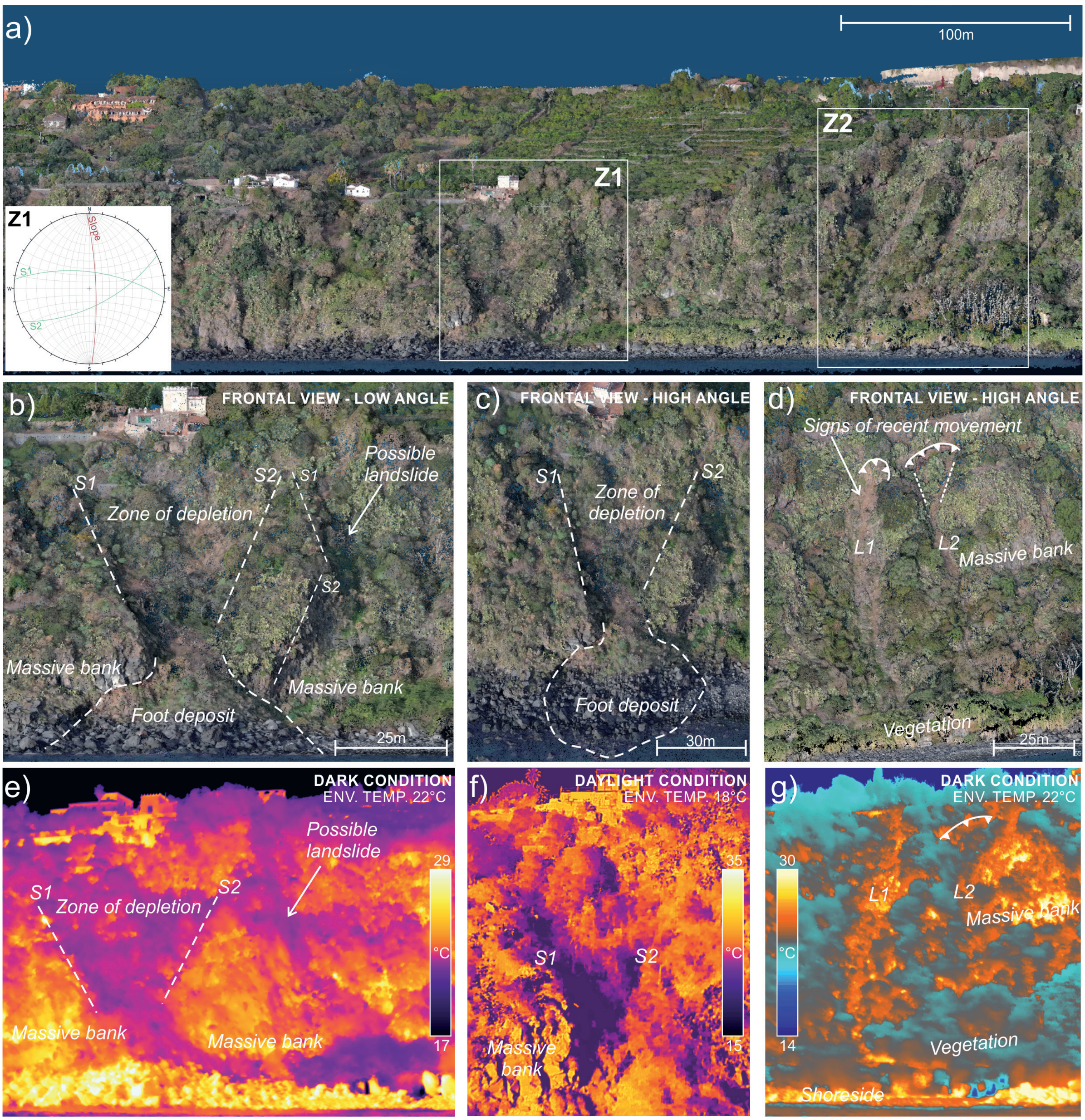

Fig. 3 - a) Panoramic dense point cloud of a TdA sector built from aerial photogrammetry; b) frontal low-angle view of Z1 focus area; c) frontal high-angle view of Z1 focus area; d) frontal high-angle view of Z2 focus area; e) thermal image of Z1 taken in dark environmental condition by boat; f) thermal image of Z1 taken in daylight environmental condition by UAV; g) thermal image of Z2 taken in dark environmental

(L2 in Fig. 3d) hosts more vegetation, thus suggesting an older age of the movement. Nevertheless, its depletion zone seems to be bordered by two structural alignments intersecting in a wedge kinematic pattern, similarly to what observed at Z1.

The IRT images framing Z1, allows the recognition of the main landslide thanks to a thermal contrast between the hollow slope portions, less exposed to the direct solar radiation during the daylight (in the period of the survey the solar radiation hit the scarp from south-east), and the protruding parts. In the first case, lower surface temperatures are preserved in dark environmental conditions (22.5-23.0°C), thus allowing the good definition of the zone of depletion (Fig. 3e). The thermal contrast allows also recognizing the wedge shape characterizing the zone of depletion, thus supporting the information retrieved from the photogrammetric dense point cloud and the preliminary kinematic assessment. The highest surface temperatures label the bare rock outcrops and the blocks laying along the shoreside. Intermediate surface temperatures (23.0-24.5°C) were measured at the foot, although this datum is affected by the uneven exposition to the solar radiation of this morphological element.

The thermal image acquired in daylight condition (Fig. 3f), from a closer position, provides a more detailed view of the zone of depletion, which keeps the lowest surface temperatures where the direct solar radiation is inhibited. Even in this case, the wedge kinematic pattern is well defined, and a certain degree of rock mass fracturing can be detected at the bare rock outcrops.

To the right, according to the interpretation provided herein, a further colder area (Fig. 3e) suggests the possible presence of a second landslide. By comparing this thermal outcome to the photogrammetric point cloud, this cold area corresponds to a further hollow, vegetated slope portion delimited by two structural segments showing a similar orientation found for S1 and S2 (Fig. 3b). Nevertheless, this morphological feature deserves a further in-depth analysis to be better defined.

Finally, the thermal photo taken at Z2 (Fig. 3g) highlights the shallow landslides thanks to the surface temperature contrast between vegetated slope portion (22.0-23.0°C) and bared surfaces (25.0-26.0°C). The highest surface temperatures were found at the massive volcanic rock outcrops (29.0-30.0°C). No specific morphological features were identified in this case, except for a circular positive thermal anomaly at the L2 crown, retracing an emptying area below a rocky outcrop.

DISCUSSIONS AND CONCLUSIONS

Results achieved by this study prove that the use of photographic techniques allows the preliminary and non-invasive landslide mapping along slopes in nature reserves, where direct surveys are limited by local restrictions. The techniques analyzed herein are characterized by a different complexity level, in terms of field execution and data processing, and show both potential and limitations. The photointerpretation of oblique images, taken by aerial surveys, allowed the quick recognition and mapping of areas affected by morphological processes connected to mass movements. At the Vernazza pilot site, significant geomorphological clues on the sea cliff stability, such as signs of past rock detachment, as well as landslide bodies and related elements, were recognized. The limitation arising from this technique is that it is a bidimensional analysis, which cannot be exploited to gather quantitative data of the examined objects. On the other hand, the photogrammetric technique overcomes these limitations since it allows the reconstruction of a detailed three-dimensional slope model, that can be examined from different perspectives. This proved useful for the landslide recognition, as well as for the definition of peculiar structural features. For example, at the TdA site, the presence of two major discontinuities intersecting in a wedge pattern was highlighted. This kinematic feature seems to be responsible of the landslide analyzed at Z1, and it was recognized also at Z2. This would suggest a sort of kinematic recurrence, that should be in-depth investigated, even enlarging the area of analysis, to assess if a recurring landslide pattern can be recognized along this peculiar escarpment. Moreover, the georeferenced dense point cloud was exploited even quantitatively, by measuring the spatial orientation of such discontinuities which, for S2, is consistent with the orientation of some tectonic structures crossing the area.

Finally, the IRT technique proved useful for the quick recognition of landslide areas along the escarpment thanks to the thermal contrast caused both by slope morphological variations and by the occurrence of different materials covering the slope (*e.g.* vegetation and bare surface). This is in accordance with previous literature studies (Mineo *et alii*, 2015) and highlights the potential of IRT as a quick landslide mapping tool. The limitation of this technique, herein applied only from a qualitative point of view, is that the images must be analysed by considering the environmental conditions. In fact, when images are taken in daylight, the slope morphology may cause thermal anomalies arising from a different slope exposition to the solar radiation. On the other hand, in a dark environment, images should be taken before the extensive cooling of the slope, which would lead to a low definition of the thermal contrasts. Nevertheless, the match between IRT and photogrammetric data is satisfactory, thus underlying how the combination of different digital surveying techniques provides reliable results in this specific setting.

This study represents the beginning of extensive surveying campaigns to be carried out in both the study sites, even with the aim of a multitemporal monitoring for the susceptibility analysis aimed at risk management purposes.

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