Rockfall susceptibility assessment for the preservation of archaeological sites in the Amalfi coast (Southern Italy) by using UAV photogrammetry

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Abstract

Rockfall susceptibility assessment is a very challenging task, being the prediction of source areas and of runout trajectories issues full of uncertainty. However, in recent times remote sensing devices, such as Unmanned Aerial Vehicles (UAVs), provided a crucial support to conventional geostructural and geomechanical approaches, especially when dealing with very steep and high slopes. In this work, the rocky cliffs of Crapolla cove (Amalfi Coast, Southern Italy) have been studied. Crapolla cove is a suggestive location, not only from a natural and landscape point of view, but also for hosting the rests of a Benedectine Abbey, dated back to the 10th century. The presence of a pebble beach at the bottom of the cove, shaped by the stream final delivery, also characterizes the area, along with two 100 m-high sub-vertical rocky cliffs impending the beach. Rock masses are affected by pervasive jointing and erosion, where tectonics/neotectonics and karst activity played a major role. As a consequence, the setting appears highly prone to rock slope instabilities. UAV-based photogrammetry has been applied in the area of Crapolla.. Two different software have been used to reconstruct the 3D geometry of the rocky cliffs, as well as quantitative information have been gained in different ways, however presenting the same results, as finally confirmed by field validation. Such data were thus plotted in a GIS environment, where a 5m-cell fishnet of the two ortophotos was created. In each cell the Markland test was executed by means of a semi-automatic workflow procedure: in such way, potential failure mechanisms of the cliffs were identified, providing useful indications to define the risk scenario and therefore to design the most suitable mitigation works, in view of a future and safe tourist access to the Crapolla area.

1 INTRODUCTION

Rockfalls are very hazardous landslide phenomena, due to their rapid kinematics and large volumes involved, spread throughout the world (Jaboyedoff et al, 2005; Hoek, 2007; Antoniou & Lekkas, 2010). Such events are peculiar of mountain and valley areas, however coastal cliffs are exposed and vulnerable to failure as well, being the combination of marine, subaerial and anthropogenic processes a main factor leading to morphological changes (Greenwood & Orford, 2007). Their dynamics is strongly influenced by spatially and temporally distributed attributes, such as detachment conditions, geometry features and mechanical properties of both rock blocks and slopes (Agliardi and Crosta, 2003). The evaluation of rockfall susceptibility is of primary importance for the safety of human lives and man-made artefacts, nevertheless, it is a challenging task when dealing with high and steep slopes. A significant aid to conventional methodologies based on field surveys is represented by digital photogrammetry, which allows to obtain 3D geometric information of steep slopes. A recent advance in photogrammetry is represented by the use of UAV (Unmanned Aerial Vehicles) systems, tools more and more relevant in the field of geological hazards assessment, especially when dealing with difficult and hardly accessible areas. UAV allow to obtain a 3D reconstruction of the slopes of interest, by means of "point clouds" and Digital Terrestrial Photogrammetry (DTP), overcoming the difficulties inherent in monitoring of high and steep slopes, or flying close to the slope in narrow areas or coastal cliffs.

In this paper, the rocky coastal cliffs of Crapolla "cove" have been investigated (Fig. 1). Crapolla "cove", located in the municipality of Massa Lubrense (Province of Naples, Italy), is a suggestive site, not only for its landscape value but also from cultural and archaeological points of view, still preserving traces of a past rich in history. In fact, at the end of a path of about 700 steps, a Chapel dedicated to St. Peter can be found, built on a Middle Age temple belonging to the Black Benedictine Monastery, whose ruins, made up of marble columns and bases, are still visible. The "cove" is characterized by the dominant presence of carbonate rocks, belonging to the formation of the Radiolitidi Limestones, Lower Cretaceous in age, formed in a carbonate platform environment. The pebble beach at the base of the cove was modeled by the torrential activity of the local watershed. The most important geomorphological elements are two carbonate rocky scarps, more than 100 m high and with evident traces of joints, due to gravity and karst action.

In view of future tourist enjoyment and of chapel restoration, a preliminary assessment of the overall stability conditions of the local slopes was necessary. To this aim, a drone-based photogrammetric survey was carried out, integrating a conventional survey campaign, which however proved to be difficult and partial, being limited to a small portion of the two cliffs. Thanks to UAV (Unmanned Aerial Vehicle) technology, and through the processing of the frames acquired, two orthophotos were obtained in frontal view, providing a first basis for the evaluation of the rocky scarp stability. In addition, a 3D model was generated, allowing the quantitative analysis of joints sets of both cliffs and the identification and definition of potential rupture mechanisms. Such step was achieved by using two different software, whose results were analyzed and compared. Accordingly, a first assessment on the stability of the area was obtained, to preliminarily evaluate the best intervention to adopt, allowing a safer future tourist enjoyment.

2 GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The Crapolla "cove" is an inlet located in the southern sector of the Sorrento Peninsula, which overlooks the Tyrrhenian Sea, between the Gulfs of Naples and of Salerno. The Peninsula, along with the Lattari Mountains, is a structural high that extends in SW-NE direction in the Tyrrhenian Sea, bounded by the deep depressions of the Piana Campana to the north and the Sele plain to the south. It also represents the southern edge of the Gulf of Naples and reaches the highest altitudes at Monte S. Angelo at Tre Pizzi (1444 m asl). The Sorrento peninsula consists mainly of Mesozoic shallow-water carbonates, which form on the Amalfi side steeper cliffs with respect to the Sorrento side (Iannace et al., 2011). The outcropping successions in the Peninsula consist of about 3500-4000 m of Triassic-Upper Cretaceous shallow-water carbonates (De Castro, 1962; Carannante et al., 2000). Cretaceous carbonates tectonically overlay Middle Miocene silicoclastic sediments of foredeep and Upper Miocene basal wedge-top deposits (Scandone & Sgrosso, 1965; De Blasio et al., 1981; Cocco & D'Argenio, 1988), generally located in the south-western portion of the Peninsula; moreover, immature turbiditic sequences cover the succession (De Blasio et al., 1981). Lastly, the stratigraphic series is locally covered by Pleistocene and Holocene pyroclastic deposits, resulting from the volcanic activity of Mt. Somma-Vesuvius (Milia & Torrente, 1997).

The Crapolla “cove” is located in the southern sector of the municipal territory of Massa Lubrense and is placed in front of three islets: Li Galli, Isca and Vetara. It consists mainly of carbonate rocks, Mesozoic in age (Figure 1). The main outcropping formation is, in fact, the Radiolitidi Limestones, dated to Upper Cretaceous Age: it is composed of alternations of gray crystalline dolomites, micritic and havana biomicritic limestones (Geological Sheet 466 Sorrento-Termini, ISPRA, 2015), has a thickness higher than 1100 m and very often appears intensely fractured. The fossiliferous content is represented by Radiolitidae, Requienidae, gastropods etc.. Further outcrops, recognizable only through in situ surveys, are represented by calcareous breccias and by slope debris. From a geomorphological point of view, the "cove" is formed by a very incised river valley, where, at its mouth end, a small beach is located. The lateral walls of the "cove", in calcareous rocks and strongly engraved by the torrential action, reach elevations above 100 m. On them, both gravitative and karst processes can be observed, typical in such contexts.

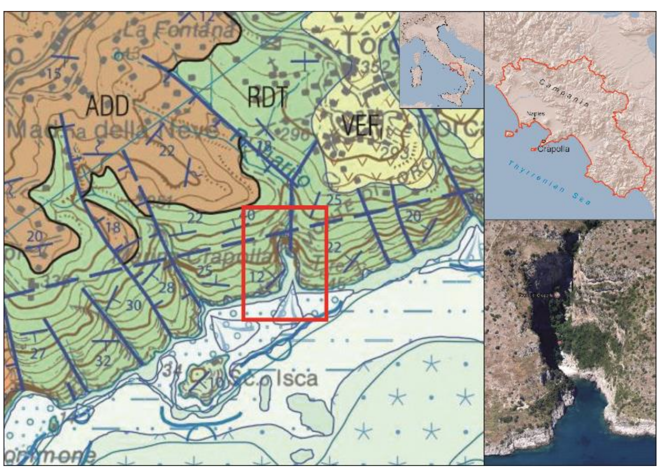

Figure 1 Geological sketch map (Sheet 466 Sorrento-Termini, ISPRA, 2015). VEF=Vesuvian-Flegrean Sintema (Pleistocene-Holocene); ADD= Deserto Sandstone (Miocene); RDT= Radiolitidi Limestone (Lower Cretaceous). In the red box, Crapolla “cove”. On top right, Campania region with Crapolla location. On bottom right, aerial view of Crapolla cove.

3 UAV PHOTOGRAMMETRY

A photogrammetric survey campaign has represented a fundamental support for the correct evaluation of the rocky scarps. Photogrammetry is, by definition, a technique that allows obtaining metric information on objects through recording, measurement and interpretation of photographic images. Its main objective is to define the shape of the photographed object and its spatial location, providing the point coordinates in a three-dimensional reference system. Among the newly developed platforms, capable to perform high-detail photogrammetric surveys and in places difficult to access, drones, or Unmanned Aerial Vehicles (UAV) represent a must. The acronym UAV describes a photogrammetric measurement platform that operates autonomously, semi-autonomously or by remote control. The aircraft can be equipped with a digital RGB camera, a thermal camera system, an infrared, a LiDAR (Light Detection and Ranging) system or a combination of various measurement systems, according to the need. The main advantage in the use of drones is due to the possibility of flying to lower heights compared to aerial photogrammetry: indeed, when a drone flies near the object, high resolution images, with a ground sampling distance (GSD, ground pixel size) of the order of the centimeter, might be obtained.

The reconstruction process was divided into three phases (Figure 2): alignment of the frames, construction of the geometry and creation of the texture. The alignment of the frames was achieved through the Structure From Motion (SFM) technique (Clapuyt et al., 2016). The methodology is based on identifying matching features in multiple images, and thus imagery overlap of at least 70 % is required. Compared to classic photogrammetry methodologies, where the location of the observing point is well established, SfM tracks specific discernible features in multiple images and, through nonlinear least-squares minimization (Westoby et al., 2012), iteratively estimates both camera positions, as well as object coordinates in an arbitrary 3-D coordinate system (Saroglou et al., 2018). In this way, the reconstruction of the three-dimensional geometry and of the camera position during the take is obtained, through frame sequence alignment. The

SFM algorithm, thus, identifies the characteristic points of the two-dimensional image and traces the same points in the following images.

At the end of this process, the program will provide three sets of data:

1. a discrete point cloud (made up of a few thousand points), which will describe the object geometry;

2. the position of the camera at the time of the frame acquisition;

3. internal camera calibration parameters.

The automatic recognition of the internal scanning parameters of the camera enables, therefore, the choice of bypassing metric cameras.

Thus, the geometry reconstruction is achieved through the creation of triangular surfaces, by using different tools. Since different levels of process quality can be set, according to this choice a greater or lower accuracy of the final product can be obtained, with a consequent increase/decrease of processing times.

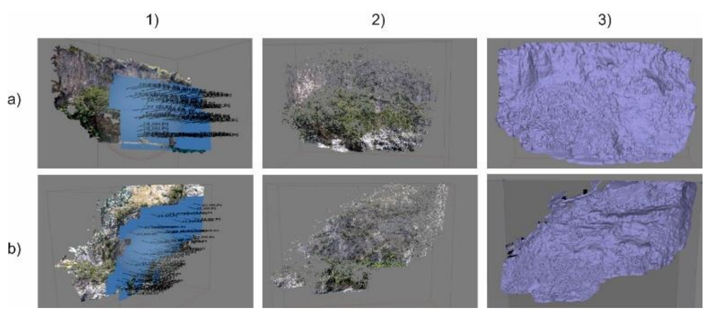

Figure 1 Frames reconstruction process for the East (a) and West scarp (b). 1) Photograms alignement; 2) Discrete point cloud generation; 3) Mesh reconstruction.

In this work two different procedures to reconstruct the 3D geometry of the study area have been followed. A first, in which the model has been obtained by using Agisoft Photoscan software, and the numerical analysis has been performed by using Open Plot (Tavani et al., 2011); a second, where both the abovementioned phases were carried out via Shapemetrix 3D, a software which enables digital rock mass characterization, including geometric measurements and geologic mapping capabilities.

4 RESULTS

The photogrammetric survey campaign, as previously mentioned, has allowed to obtain two orthophotos with a frontal view of both rocky walls under analysis. Thus, 63 frames were acquired for the East scarp and 87 for the West scarp. During the flight phase, the perspective views of the wall were examined and images, generated with different frames, were acquired, to obtain a complete view of the front. The various takes enable higher precision and detail of the point cloud, necessary to obtain the three-dimensional study model achieved with the both software. It is worth to underline that "virtual" data have been confirmed during field survey, conducted on a small accessible portion of both the scarps of interest: in this case, 2 scan lines have been performed, one 3 m-long, on the West slope, and the other one 1m-long on the East side.

4.1 Photoscan + Open Plot

In a first step, the alignment of the frames was performed. Subsequently, the generation of the scattered cloud, or the basic geometry of the walls, was obtained. This was made up of 61,799 points, for the East scarp, and 57,304 points for the West scarp. Later, thanks to the high computing capacity of the available PC, the reconstruction parameters used were set to obtain the maximum qualitative yield: the dense cloud of points was then created, composed of 4,673,177 points for the East and 5,114,592 for the West scarp. From the latter, by means of triangulation processes, the model surface has been extracted, the so-called mesh: with this term we usually indicate a vector data format consisting of the set of vertices, edges and faces that define the shape of an object in the 3D modeling field.

From the 3D model generated, the jointing state of the rocky walls has been analyzed by means of the open source software Open Plot (Tavani et al., 2011). It must be underlined that only joints > of 50 cm have been taken into account, due to the model resolution. For the West and the East scarp, 213 and 411 joints have been recognized respectively. Two stereonets have been drawn for both the slopes: the East scarp is characterized by the presence of a set of joints, having a NE/SO direction, while the West scarp shows 2 joints families, one with orientation E/W and the other one with WNW/ESE direction. Moreover, on this side, layers data have been taken, showing an average dip direction of N220 and dip angle of 20°. Both slopes have joint families characterized also by a very high dip angle: the East Scarp present values between 70 and 90°, while the West Scarp shows dip angle values between 60 and 90°.

4.2 Shapemetrix 3D

The reconstruction of the geometry of the slopes has been achieved by using the add-on Shapemetrix UAV, which exploits high quality photographs taken from calibrated camera controlled by aircraft. Here as well, 63 and 87 frames from the East and the West scarp were used, generating a point cloud of 5.9 and 6.4 million points, respectively. The quantitative analysis on jointing of the area has been carried out through the add-on JMX Analyst. On the East scarp (Figure 3), 345 joints have been recognized, characterized by an average length of 5 m, and for a total length of 1750 m. Here, a family with average dip direction of 150° and average dip angle of 89° is recognized. Also 145 measurements of layers recognizable by photogrammetry have been taken. In this case, the average dip direction is 76° with a dip angle of 12°. On the West scarp (Figure 4), 177 joints have been identified. Two families have been distinguished: a first one, with orientation NW-SE and dip angle between 55 and 90°, and average length of 4 m, from a minimum of 0.5 to a maximum of 17.5 m; a second one, with orientation NNE-SSW and dip angle between 70 and 90°. In this case the average length is of 3 m. Layers data, derived from 108 acquisitions, show an average dip direction of 170° and dip angle of 1°. JMX analyst enable also the estimation of the volume of sectors which may trigger rockfalls or sliding. On the East scarp, 14 sectors have been selected, according to joint presence and orientation, obtaining an average value of 9 m^3 for each block. For the West scarp, 27 portions have been identified, having an average volume of 11 m^3. Volume data will be useful for future investigations, dealing with the kinematic analysis of rock blocks trajectories

All the data gathered are resumed in Table 1 and 2.

Table 1. Main data for the East Scarp.

Feature	Parameter	Value
Joint J1	Dip Direction	150°
Joint J1	Dip Angle	89°
Joint J1	Average Length	5 m
Layers	Dip Direction	76°
Layers	Dip Angle	12°
Blocks	Average Volume	11 m^3

Table 2. Main data for the West Scarp.

Feature	Parameter	Value
Joint J1	Dip Direction	127°
Joint J1	Dip Angle	85°
Joint J1	Average Length	4 m
Joint J2	Dip Direction	190°
Joint J2	Dip Angle	81°
Joint J2	Average Length	3 m
Layers	Dip Direction	170°
Layers	Dip Angle	1°
Blocks	Average Volume	9 m^3

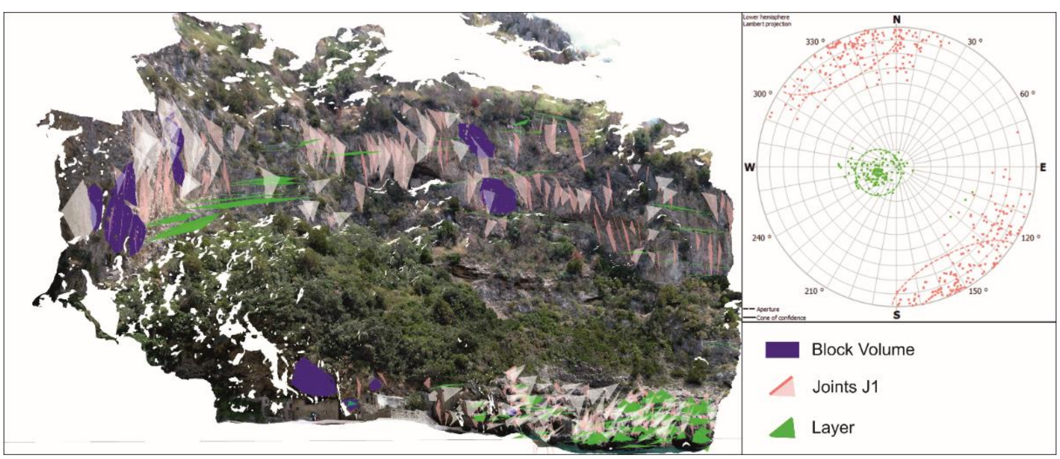

Figure 3 On the left, 3D frontal view of the East scarp with the geo-mechanical data collected. On the right, stereoplot of the East scarp.

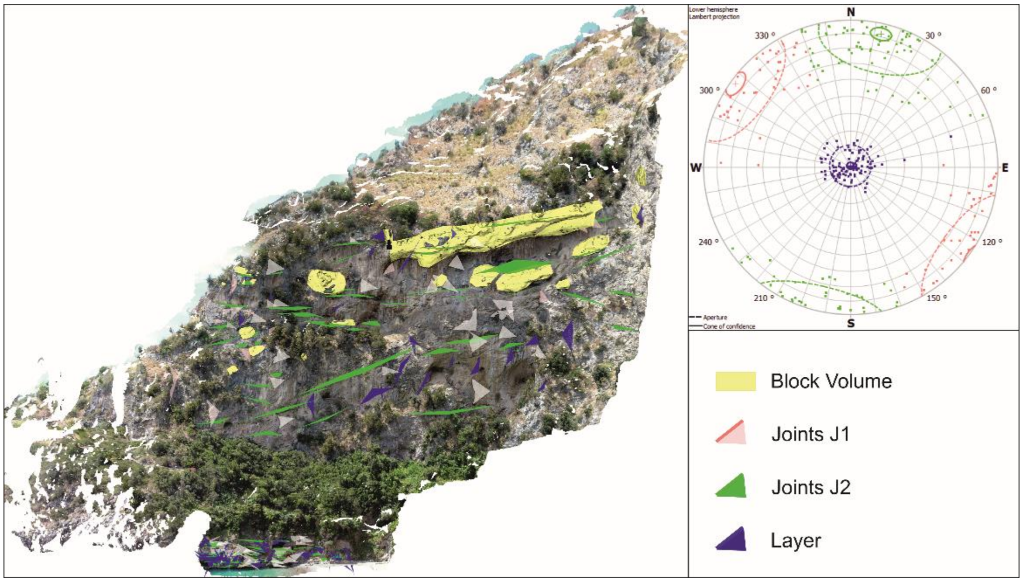

Figure 4 On the left, 3D frontal view of the West scarp with the geo-mechanical data collected. On the right, stereoplot of the West scarp.

4.3 Susceptibility model

In order to obtain a photogrammetry-based susceptibility model of both scarps, all the available data have been analyzed in a GIS environment. First, two TIN (Triangulated Irregular Network) models have been generated by means of topographic maps in frontal view generated by photogrammetry elaboration. From the TIN models, DEM (Digital Elevation Model) and thus the slope value of each cell (of 5×5 m) have been obtained. Both the elevation and the slope values have been re-projected along the vertical axis in order to have correct data and to integrate them with the joint network previously analyzed. To this aim, joint data were also reported in a GIS environment, finally obtaining a complete view of both rocky cliffs with all data available. Both slopes were discretized in a fishnet of 5×5 m cells, in which each cell contains information about coordinates, slope, dip direction and angle of the joints or part of them joints. Giving all these data, Markland test (Markland, 1972) was carried out taking into account the cells derived from the fishnet. Only cells containing fractures with dip direction ±20° with respect to that of the entire slope have been considered in the analysis; as for the friction angle, a value of 40°, derived from Budetta & Calcaterra (1991), who studied the calcareous rocks of the Sorrento Peninsula, has been selected. The final result is a discrete analysis of both the rocky cliffs. For the East Scarp (Figure 5), on a total of 329 cells where rocks are outcropping (162 cells are related to vegetation only), 4% (14) are identified as potentially affected by plane failure, as derived from Markland Test; 10% (31) are potentially involved by falls, heuristically identifying those areas where a calcareous breccia, characterized by chaotic structure, and karst cavities are present; 86 % (284) are stable. For the West Scarp, excluding those cells covered by vegetation (20%, 152 cells), on a total of 596 rocky cells, 7% are potentially affected by plain failure (41), 4% by falls (23) and 89% can be considered stable.

5 DISCUSSION

The availability of a UAV device has permitted a complete analysis of the Crapolla cove area, whose rocky scarps, ca. 100 m high, endanger an area with a relevant touristic potential, being located in the Amalfi coast, and due to the presence of significant archaeological remains of the Middle Age. The qualitative analysis, carried out on the two sides of the Crapolla “cove”, has highlighted the presence of several areas with a high density of joints and erosion forms. From the geo-structural quantitative analyses conducted, the presence of a joint family on the East scarp and of two sets on the West scarp, in addition to the bedding, has emerged, highlighting a scenario of potential instability in the area. It is worth to underline that the results derived from both the software used for the extraction of quantitative data were in total agreement between them and with field data, confirming the fundamental support given by virtual outcrops analyses. The elaboration of a susceptibility map of the two scarps, containing the information derived from the virtual 3D data, has permitted a more precise analysis of the potential rock detachment source area. In this sense, through Markland test we were able to identify 4% and 7% of the East and West scarp, respectively, as potentially affected by plain failures; through a qualitative analysis, 10% and 4% were recognized as involved by falls, identifying those area where calcareous breccia and

karst cavities are present. Summing up the total surface of the two vertical cliffs, 12% is susceptible to rockfalls mechanism, a figure which underlines the predisposition of such rock formation to landsliding. The area of Crapolla, thus, according to this preliminary study, has shown critical issues that must be object of further and more accurate studies. Indeed, in view of a future and more recurrent touristic enjoyment, numerical analyses must be improved, implementing, for instance, numerical codes which evaluate rock trajectories and end points and providing precise indications about possible interventions to reduce the related risks.

6 CONCLUSIONS

The area of Crapolla, characterized by the dominant presence of two carbonate scarps, is a site with great touristic potential, although threatened by rockfall-susceptible high cliffs. The preliminary analysis over the area, conducted using UAV-based photogrammetry integrated with conventional geo-mechanic methods, has highlighted that ca. 12% of the area of Crapolla area is potentially susceptible to rockfall mechanisms. The use of UAV has represented a fundamental support, being the area very high and very steep, and proved to be valuable in collecting detailed qualitative and quantitative data. It is worth to underline that field surveys are always necessary to validate the goodness of the 3D models and to integrate data when virtual data are missing or corrupted. In conclusion, the integration of virtual and conventional data here shown is

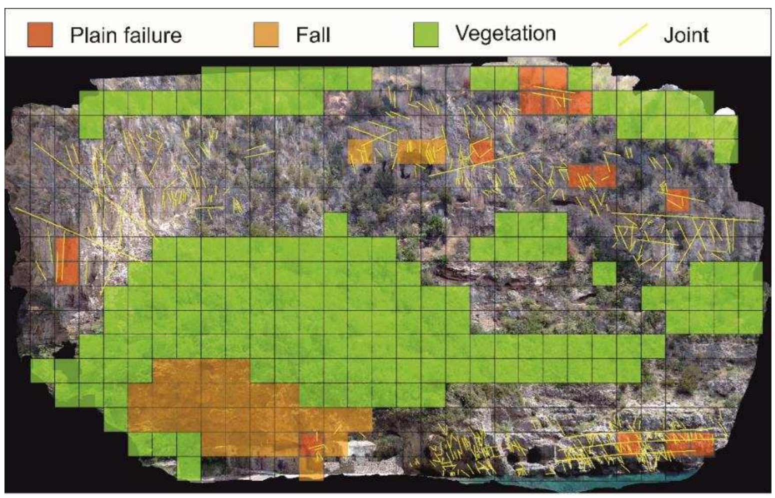

Figure 5 Susceptibility model for the East Scarp.

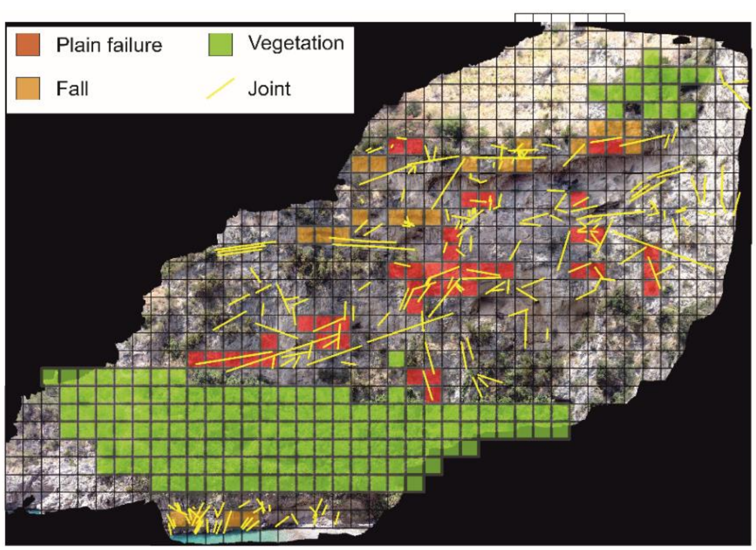

Figure 6 Susceptibility model for the West Scarp.

fundamental for detailed analysis, aiming at the future assessment of the rock trajectories which may provide support to the design of mitigation works, in view of a future touristic enjoyment of the Crapolla cove area.

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