Multi-approach for the assessment of rock slope stability using in-field and UAV investigations

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ABSTRACT

The present study is aimed at analysing the rockfall phenomena involving a carbonate rock scarp in San Donato di Ninea village (Calabria, south Italy), where some buildings and a portion of a road are exposed to a high hazard condition. The geomechanical investigations of the rock scarp were performed through a multi-approach based on infield investigations, geophysical surveys and high resolution of images acquired by a drone. The achieved data allowed to assess the quality of the rock mass and the susceptibility of rock slope to failure through the Rock Mass Rating and the Slope Mass Rating classifications respectively. The obtained results showed slope conditions ranging between unstable and completely unstable. Geophysical surveys allowed to investigate the subsurface material and showed a high jointing rock mass in the shallower portion. In order to acquire the potential change in geomechanical features on the whole escarpment rock, high-resolution images were acquired by a drone. Thus, a 3D dense points cloud model was reconstructed in a setting of high accuracy based on 55 million of points with a density of 748.85 points for m^2. The 3D model was imported into CloudCompare software to extract the geological planes through FACETS plugin, which allowed to recognize the jointing sets on the whole surface of rock escarpment. The digital data were compared with the ones collected by scanline method in order to verify their soundness and further detailed digital investigations were carried out on human inaccessible areas to examine the corresponding fracturing degree.

Keywords: *Geomechanical characters; Rock mass classification; Rockfall; UAV; 3D cloud point; Calabria, Italy;*

1. - Introduction

In the last decades, landslide damage has increased worldwide due to the population growth that caused a large urban expansion also in landslide prone areas (e.g., Petley 2012). Among the instability types, rockfall is the fastest type of landslide characterized by high value of impact energy (Varnes, 1978) and it is the most frequent type of instability on steep slopes both in mountain areas (e.g., Fischer et al., 2012; Wang et al. 2020) and coastal cliffs (Ietto et al., 2015, 2018; Li et al., 2019). These instability phenomena can be induced by earthquakes, freeze-and-thaw cycles, heavy rainfall and progressive weathering processes on rock materials in suitable climatic conditions, involving from limited to large rock volumes (e.g., Romeo et al., 2017; Piciullo et al., 2018; Conforti and Ietto 2019, 2020). Several researchers have focused a growing interest in the analysis of likelihood of release, rockfall path, height, volume and energy of rockfall impact (e.g., Pérez-Rey et al., 2019). In urbanized areas, these phenomena can make serious damage to isolated house or entire villages, long stretches of roads, railways or other anthropogenic facilities causing fatalities and considerable economic loss (Guzzetti, 2000; Conforti and Ietto, 2019; Wu et al., 2019). For these reasons, rockfall protection through structural or non structural solutions (e.g. land-use planning) becomes an important issue for administrators and stakeholders, making necessary a reliable and accurate landslide modelling (Straub and Schubert, 2008; Agliardi et al., 2009).

The high velocities and unpredictability of rockfall makes this phenomenon among the most dangerous worldwide geological hazards (Li et al., 2019). The complete mitigation of the rockfall hazard is frequently difficult, due to the frequency and magnitude changing temporally and spatially (e.g., Strunden et al., 2015). Furthermore, the assessment of rockfall hazard is limited by poor availability of high-resolution discontinuity geospatial data, of rockfall release points and of block geometry on the scarp. This lack of data occurs because, often, the geological features in the source areas cannot be easily identified due to the inaccessibility of the areas (e.g., Dorren, 2003; Pérez-Rey et al., 2019). Indeed, the reliability of rockfall hazard assessment depends on the quantity and quality of available data (Pradhan et al., 2014). Hence, in situ traditional geomechanical investigations need to be improved using new technologies. In this regard, time series of high-resolution remote sensing images from satellites, drone or laser scanner techniques are recently widely employed for discontinuity measurements, for kinematic analysis and to estimate the proneness of scarps to rock block instability (Zhang et al., 2019; Depountis et al., 2020; Li et al., 2020). These recent studies testify the great attention paid to the topic by the scientific comunity worldwide. Among these, the Digital Terrain Model (DTM) is widely employed both to investigate and to monitor landslide areas (Conforti et al., 2021 and references therein). In this regard, Differential Synthetic Aperture Radar Interferometry (DInSAR), Light Detection and Ranging (LiDAR), Global Navigation Satellite Systems (GNSS), 3D laser scanner and Unmanned Aerial Vehicles (UAV) are the main techniques employed for the acquisition of high-resolution landslide terrain data, which are useful to the construction of a DTM (Cigna et al., 2016; Wasowski et al., 2017; Mury et al., 2019; Confuorto et al., 2019; Conforti et al., 2021). In the last decades, the UAV found a wide employment in the application of landslide studies due to the following advantages: i) availability of high-resolution and low-cost images; ii) simple and fast applicability; iii) flexible survey planning (Borrelli et al., 2019; Conforti et al., 2021). Therefore, the use of a multi-approach, based on classical field geomechanical investigations and digital high-resolution images, can bring remarkable advantages to identify the stability conditions and the hazard level in sites prone to rockfalls.

In this framework, this paper proposes a comprehensive assessment of the stability condition of a rocky scarp in San Donato di Ninea village (Calabria, southern Italy) (Figs. 1a and 1b). The study area consists in a meta-limestone scarp affected by widespread rockfall phenomena, which pose several buildings and a municipal road under high-risk conditions. In order to mitigate the rockfall hazard and to plan the adequate engineering solutions, a detailed study of the geological, geostructural and geomechanical conditions was performed on the examined rocky scarp. The study was carried out through several steps, as following: field investigations, based on geomorphological, geostructural and geomechanical surveys; application of rock mass classifications using the classification schemes proposed by Bieniawski (1989), Romana (1985) and Hoek and Brown (1997); seismic investigations; use of high-resolution images acquired by a Drone, that allowed to obtain a point cloud model and the construction of a Digital Terrain Model (DTM); application of the open-source CloudCompare software, using the FACETS plugin, to extract the bedding planes, isolate the discontinuities and assess the state of fracturation in the rock mass. Therefore, this research uses a multi-approach that provides a sufficiently quick and low-cost analysis of rockfall phenomena providing a comprehensive understanding of the hazard conditions. The used approach may assist and help the competent authorities and stakeholders in making decisions about the management and protection of urban areas and infrastructures through the employment of hazard mitigation strategies.

2. - Geological framework

The Calabria Arc (CA), in south Italy, is a continental crust fragment originated during the closure of the Tetide ocean, which was caused by the collision between Europe and Africa plates (e.g., Tortorici, 1982; Ben Avraham et al., 1990). Afterwards, both slabs pull and east southeastward rollback of the CA consumed part of the Mesozoic Ionian Basin, giving rise to the Neogene Tyrrhenian basin. As a result, the southern part of the Calabria forearc collided with the E-W striking African continental margin, forming the Maghrebides; whereas, the northern part collided with the S-E striking Apulian margin, forming the Apennines. (Reitz and Seeber, 2012; Filice and Seeber, 2019). Rapid regional uplift, longitudinal extension and about 20° clockwise rotation of the CA are prominent manifestations of its reorganization starting since the second half of the Pleistocene (e.g., Westaway, 1993; Ietto and Bernasconi, 2005; Reitz and Seeber, 2012; Filice and

Seeber, 2019 and references therein). The present-day crustal deformation of the CA is mainly represented by extensional tectonic lineaments, ESE-WNW and WSW-ENE oriented, dislocated along the entire Calabria orogen (Westaway, 1993; Tortorici et al., 1995; Monaco and Tortorici, 2000).

In literature, the CA is subdivided in the northern and southern sectors, separated by the Catanzaro and Mesima graben (e.g., Tortorici, 1982). The two sectors differ in the tectono-stratigraphic setting of constituent geological units, in the structural features and in the tectonic evolution (Scandone, 1982; Tortorici, 1982).

The study area falls in the northern sector of the CA (Fig. 1a), which is constituted by a nappe system composed by three main tectonic complexes: the Apenninic Units at the base, the Ophiolitic Units in the intermediate position and the Continental Units at the top of the nappe edifice (Amodio Morelli et al., 1976; Filice et al., 2015). The basal Apenninic Units mainly dominate in the northernmost part of the Calabria region and they are constituted by Triassic-Early Miocene successions representative of the Africa continental margin (Amodio-Morellietal., 1976; Iannace et al., 2005, 2007¸ Filice et al., 2015). In particular, among the Apenninic Units, the San Donato Unit (Amodio Morelli et al., 1976; Ietto and Barillaro, 1993) or Lungro Verbicaro Unit (Iannace et al., 2005, 2007), represents the lowermost unit and is dominant in the study area. This Unit consists of a succession of siliciclastic and carbonate rocks ranging from Lower to Upper Trias in age (Amodio Morelli et al., 1976; Ietto and Barillaro 1993; Ietto and Romano, 2001). The entire San Donato sedimentary succession was affected by several deformation phases and by Alpine metamorphism, reaching HP-LT facies conditions (Iannace et al., 2007). Several magmatic events, represented by metabasite dykes, extensively intrude the carbonate sequence and were ascribed to Middle-Upper Trias (Barca et al., 2010).

From a tectonic point of view, the study area is located in the north-western sector of the Crati Basin. The Crati basin is a graben dominated by extensional N-S oriented tectonic features (Brozzetti et al., 2017). It is delimited by the Catena Costiera-Pollino ridge on the north and west sides and by the Sila Massif on the east side (Fig. 1b). The Crati Graben marks the outermost clear structural expression of inner Calabria forearc extension (Filice and Seeber, 2019).

The studied area is located in San Donato di Ninea village (Calabria, south Italy), which is close to the Sangineto-San Sosti tectonic lineament (Amodio Morelli et al., 1976). In particular, three main normal faults alignments, striking NNE and dipping toward SE, have been recognised in this sector (Fig.1b; Brozzetti et al., 2017). The westernmost fault, the San Sosti-Saracena fault-alignment, is about 25 km-long and it is responsible of the contact between the Crati Graben filling deposits and the San Donato-Verbicaro metacarbonates. This important fault-alignment is located approximately

1 km from the study area (Fig. 1b). The latter is constituted by a rock scarp made up of meta-limestone and white microcrystalline dolomite (Fig. 1c) ascribed to the San Donato Unit (Ietto and Barillaro, 1993) or Lungro Verbicaro Unit (Iannace et al., 2005, 2007) (Fig. 1d). This carbonate rock mass is intensely fractured, and at the foot of the escarpment, a talus slope covers the basement rock (Fig. 1c). The talus deposit is composed by heterogeneous carbonate rock fragments ranging from few centimeters to more than 1 meter in sizes. Frido Unit (Bonardi et al., 1988), constituted by dark or greenish phyllite (Middle Triassic in age) or locally by quartzites and calcschists, outcrops extensively in the studied area, as well (Fig. 1c). NE-SW and NW-SE striking normal faults cross the study area, giving rise to a fault scarp oriented like the second fault system (Fig. 1c). The escarpment is about 100 m high and it is affected by several rockfall phenomena, which expose the downslope urbanized area to a high risk condition.

3. - Methodology

Several authors argued on the instability processes affecting various rock types, stating that the collection of accurate geological, geomorphological, geophysical and geomechanical parameters is necessary for a reliable analysis of the phenomena (e.g., Calcaterra and Parise, 2010; Ietto et al., 2016). The present research was based on in situ and aerial investigations in order to achieve a detailed geological modelling of a rock escarpment affected by rockfalls. The investigations were organized as following: (a) detailed field surveys aimed at mapping instabilities and recognising both the structural framework and the lithologies involved in instability processes; (b) geomechanical investigations; (c) seismic refraction traverses; (d) use of a drone to collect high-resolution images of landslide area. The used approach is summarized in the flowchart in Figure 2, which shows that the use of drone technology allows to investigate wider areas with respect to the classical in situ surveys that are restricted to limited zones. Thus, the employment of both survey methodologies allows to provide a complete and detailed assessment of the geostructural conditions in wide areas, providing that a validation of the digital survey results is carried out by means of the in-situ survey. The different steps of the used methodology are described below.

3.1. - Field investigation

The first step of the field investigations consisted in the identification and mapping of the instability phenomena. The landslides were identified through the combination of aerial photographies, landslide inventory of the Basin Authority of the Calabria region and detailed field surveys. Landslide typologies were classified according to Cruden and Varnes classification scheme (1996) and the collected data were employed for the construction of a landslide inventory map.

Detailed structural and geological field investigations were also carried out to map the tectonic lineaments and the rock types involved in instability processes.

Since the discontinuity characteristics control the slope stability and geomorphic development (Gumede et al., 2007; Conforti and Ietto 2019), a detailed geomechanical investigation was performed in order to collect the main features of the discontinuities in the rock slope. The discontinuity survey was carried out at three measurement stations (Fig. 3), which well represent the fractured state of the rock mass. The measurement stations were located as following: 2 in the upper part of the slope and 1 close to the municipal road, where the road cuts allow a good observation of the geostructural features of the rock masses (Fig. 3). The discontinuity orientations of the rock slope were measured along a reference line at 1.60 m above the ground level. The scanline method was applied to collect the joint characteristics in each measurement station, enabling to achieve more data than other survey methods because it more effectively accounts for variance in the joint properties (Gumede and Stacey, 2007; Şen, 2014; Alavi Nezhad Khalil Abad et al., 2016). Following the recommendations of Priest and Hudson (1981) and I.S.R.M. (2014), the length of the scanline was set between 6 and 10 m. The joint characteristics (including orientation, , distance between discontinuities, trace length, Schmidt hammer rebound, roughness, aperture, , infilling material, and water condition) were collected according to I.S.R.M (2014) in each measurement station. The joint orientation data (dip/dip direction) were measured using a digital compass-clinometer App for portable device performed by Midland Valley & Petroleum Experts (“Fieldmove” App for tablet). This App was installed on an Apple iPad5 mini wifi-cellular (64 GB memory) with an internal A-GPS GLONASS/GNSS. All the measurements were done according to Midland Valley (2014) placing the mobile on the rock surface and directly measuring with the FieldMove App. The measurement errors were estimated at ± 2° for dip directions and ± 1° for dip angles (Novakova and Pavlis, 2017). The joint orientation data (dip/dip direction) were analyzed by Stereonet v.11 software (Allmendinger, 2020) in order to define the dominant joint sets. Finally, the dominant joint sets were plotted on the stereonet and examined using the Geomeccanica software, performed by Aztec Informatica, with the scope to analyze the possible kinematic failure modes controlled by the various discontinuity planes. In this regard, the basic friction angle was estimated through direct shear test according to I.S.R.M. suggested methods (I.S.R.M., 2014). The average joint roughness value was defined for each joint set through a profilometer and the classification scheme proposed by Barton (1976). Finally, for each set, the collected joint features were analyzed by simple statistical methods.

3.2. - Rock mass classification

The collected geomechanical data were employed in well-known classification schemes (Bieniawski, 1989; Romana, 1985; Romana et al., 2015; Hoek and Brown, 1997) to obtain an assessment of both the rock mass quality and the slope proneness to instability phenomena. In particular, the Rock Mass Rating (RMR) system was applied, according to the methodology suggested by Bieniawski (1989), in order to obtain the characterization and evaluation of the rock mass quality. The Bieniawski methodology recognizes five classes of rock mass quality, ranging from very good rock (class I) to very poor rock (class V) on the basis of the basic RMR (RMRb) index. The latter was computed in each geomechanical station by the sum of the first five parameters of the RMR system: strength of the intact rock, rock quality designation (RQD) rating, joint spacing, joint conditions and hydraulic conditions. The strength of the intact rock was obtained by point load tests according to the methodology prescribed by I.S.R.M. (2014). The test was performed on several rock samples well representative of the meta-limestone forming the rock scarp. The RQD rating (Deere and Deere 1988) was estimated through the methodology proposed by Palmström (1982), which correlates the RQD index and the discontinuity characteristics. Palmström methodology well represents the fracturing state of the rock mass and is more accurate than other methodologies (e.g., Priest and Hudson 1981; Sen and Kazi 1984; Şen 1993; and many others). Hydraulic conditions, spacing, and morphology of the jointing needed to calculate the RMRb index are previously collected in the geomechanical survey.

Since the RMRb system was originally elaborated by Bieniawski (1984) for the estimation of rock mass properties in underground excavation, the further application for slope stability assessment was provided by Romana (1985) with the Slope Mass Rating (SMR) index. The latter is a modification of the RMRb and includes three correction factors based on the discontinuity orientation, providing a preliminary assessment of the susceptibility to failure of the rock slopes. In the last 30 years, the SMR index was widely employed on artificial slopes (i.e., road-cuts), providing efficient results (Romana et al. 2015). The SMR system was applied in all measurement stations.

Geological Strength Index (GSI in Hoek and Brown 1997) was estimated in the three measurement stations following the methodology suggested by Hoek et al. (2013). The GSI is a useful tool for the assessment of the rock mass strength in different geological conditions, providing a careful engineering geology description of the rock mass. It is largely used in tunnels, foundations, slopes and road-cuts through a visual examination of rock masses exposed by excavations (Marinos et al. 2005).

3.3. - Seismic survey

Several authors (e.g., Olona et al., 2010; Ietto et al., 2016) asserted that seismic investigation is a suitable tool to detect subsoil features in the rock masses, such as thicknesses of layers, mechanical properties and their gradual change with depth. So, the geophysical survey can provide results useful to a better understanding of the geological subsoil modelling in the rock mass. The method is based on the analysis and interpretation of the first arrivals of critically refracted or reflected waves in order to provide a 2D P-wave velocity model. In the studied area, two high resolution shallow seismic refraction profiles were performed. In particular, one of the seismic traverses was performed in the upper part of the slope (lineament 1 in Fig. 3) and its length was 60 m, reaching a depth of about -20 m. The same length and depth also characterize the second seismic refraction traverse, carried out in the lower part of the slopes (lineament 2 in Fig. 3). A seismic model was produced for each seismic profile, using only first-arrival times (P waves).

Seismic refraction data were acquired by a 24-channel Pasi Gea24 seismograph equipped with 4.5 HZ vertical geophones. Twenty-four vertical geophones were positioned along the profiles at 2.5 m intervals. The necessary seismic energy was produced by hammer blows (10 kg weight) on a metal plate and seven shots were delivered in each trasverse (shot distances: 0.0, 8.75, 16.25, 31.25, 46.25, 53.75, 62.50 m). The refraction surveys were carried out following the standards prescribed by A.S.T.M. (2018). Seismic analysis of refracted P waves was carried out by means of the Seisimager/2D version 3.3 software package, using Pickwin and Plotrefa modules. The results provided useful information about the changes of geomechanical state with depth.

3.4. - Drone investigations

Unmanned aerial vehicles (UAVs) are widely used for scientific research, commercial and recreational aerial photography (Lucieer et al., 2014; Mury et al., 2019). In this research a Quadcopter Phantom 4Pro model with four-rotor, produced by Dà-Jiāng Innovations (DJI) Technology Company was used. The UAV was equipped with a high-resolution camera supplied with a CMOS (complementary metal oxide semiconductor) image sensor of 20 Megapixel and standard wide-angle lens of 24 mm. The used UAV has a flight duration of 30 min and it is gifted of an onboard autopilot system including a GPS system and ultrasonic optical altimeter; this navigation system receives signals from GPS/GLONASS constellation. Several automatic and manual flights, with a height ranging from 40 to 50 m with respect to start point, were carried out. Thus, a number of 883 photos were acquired (Fig. 4a), keeping sufficient overlap (80–90%) from different angles and positions as recommended by Lucieer et al. (2014). Figure 4b shows the density map of the photograph footprints. In order to obtain a better georeferencing of the aerial photogrammetry, 13 Ground Control Points (markers) (Figs. 4c and 4d), visible by the UAV, were used. Geographic coordinates of each marker were obtained through a ground differential GPS receiver system (Fig. 4d), using a Trimble apparatus. WGS84 was the reference system used for GPS data. A further correction of the marker geographic position was performed by a Virtual Reference Station (VRS), providing an error position in a range of 1-2 cm. All acquired images were processed by an appropriate software based on an automatic feature detection algorithm called SIFT (Scale Invariant Feature Transform), which was developed by Lowe (1999). The feature corresponds to a distinctive area of image texture, which is identified in other images (Lowe, 2004; James and Robson 2012). SIFT algorithm produces sparse point-clouds, which represent the most prominent features within the image set, allowing a construction of a 3D image (e.g., Snavely et al., 2008; Gupta and Shukla 2018). In the studied area, the image set provided a point-cloud constituted by 55 million of points, with a density of 748.85 points for m^3. The UAV point cloud corresponds to a Digital Surface Model (DSM) that was used to derive a meshed 3D model. The latter permitted the construction of the Digital Terrain Model (DTM), having an average resolution of 1.85 cm/pixel, able to provide aerial images of the rock slope with different view angle. Open-source CloudCompare software, with the aid of FACETS plugin (Dewez et al., 2016), was employed to analyse the 3D model of the rock scarp in order to extract the discontinuities of the rock mass on the basis of dip direction and dip angle. In particular, the 3D dense cloud point, generated from the photogrammetry process, was the input file to the CloudCompare software. FACETS plugin was used to divide the point cloud into sub-cells and, then, to identify elementary planar objects (e.g. fracture planes) and aggregate them progressively into polygons according to a planeity threshold. Details of the principles, functions and capabilities of FACETS plugin can be found in Dewez et al. (2016). This approach provides useful information on the fracturation grade and on the discontinuity sets perfectly comparable with the ones obtained by scanline survey method (Dewez et al., 2016; Nagendran et al., 2019).

4. - Results

4.1. - Geological and geomorphological investigations

Geological field surveys showed that the dominant lithology in the study area is represented by meta-limestone and dolomite rock masses outcropping in a tectonic window with respect to the Frido Unit (Fig. 1d). The examined scarp is located close to the intersection of two faults, NE-SW and NW-SE oriented (Fig. 1c), which strongly influence the discontinuity sets. The latter are characterized by slightly rough or slicksided joint surfaces due to weathering processes that produce a further fragmentation and disintegration of the rock masses. Steep slope, with a slope angle greater to 75° (Fig. 5b), characterizes the scarp partially covered by Mediterranean bush (scrub, bushes, and rare trees). A smooth and gentle topography is observed only towards the top of the scarp.

The geomorphological investigation provided detailed data about the spatial distribution of the mass movements in the studied area. So, the collected data were employed for a better definition of the previous knowledge about the landslide scenario (Fig. 5a). In particular, the geomorphological investigation allowed to re-define both the landslide geometries and the hazard conditions identified in the “Hydrogeologic Setting Plan” of the Calabria region (PAI Calabria, 2001) where the landslide hazard areas were under-estimated. In the surrounding area the recognized landslide types are mainly slide-type and rockfall phenomena (Fig. 5a).

Rockfall-type instability dominates in the steeper slopes such as the studied scarp, while a talus slope characterizes the downslope area. The talus is composed by different sizes of carbonate rock blocks, ranging from few decimeters to greater than 2 m. Field evidences indicate that the instability phenomena are still active, as shown by the presence of fresh scarps and widespread open fractures along the scarp, producing dangerous rock masses highly jointed (Fig. 6). This geomorphological contex represents a high hazard condition for the buildings and infrastructures located in downslope area. Indeed, the whole eastern side of the San Donato di Ninea village is marked as high hazard area by the Hydrogeologic Setting Plan of the Calabria region (PAI Calabria, 2001). For these reasons, several solutions of hazard mitigation were employed along the slopes, such as wall and wire mesh retaining structures (Fig. 3). Furthermore, slide-type landslides are present on the eastern side of the San Donato di Ninea village affecting the valley areas with respect to the municipal road (Fig. 5). These processes show deeper (> 5m) failure surfaces involving mainly the phyllite rocks, belonging to the Frido Unit, and subordinately the carbonate formations of San Donato Unit.

4.2 - Discontinuity characteristics and rock mass classification

A careful discontinuity investigation, concerning the collection of jointing features, was performed through three measurement stations along the investigated escarpment (Fig. 3). The joint surveying was carried out to define the geomechanical properties of the rock mass and to assess the potential stability conditions of the rock scarp through the application of Romana’s classification method (Romana, 1985, Romana et al., 2015). The analysis of the collected discontinuity orientations showed the presence of four dominant joint sets in all measurement stations. The dominant joint sets and slope face orientation of each measurement station were plotted on equatorial equal-area diagrams (Fig. 7), where the joint set 1 is characterized by the highest number of discontinuities in all measurement stations. The other joint sets have similar orientations in the three measurement stations but the relative number of discontinuites is different because slope face orientations are different that influences the occurrence of discontinuities along the scanline. So, the numeration of the other joint sets on the stereonets (Fig. 7) was assigned on the basis of similar orientations, as showed in Table 1. Only the station 3 shows a joint set which results absent in the other measurement stations. The rock slope kinematic analysis revealed that planar failures are likely to occur in measurement stations 2 and 3, instead, wedge failures in the measurement stations 1 and 3 (Fig. 7).

In all measurement stations, in addition to joints orientation, Schmidt hammer values acquired on natural rock walls, as well as discontinuity features (such as distance between discontinuities, roughness, aperture, trace length, infilling material and groundwater conditions) were collected. All geomechanical data, measured during field investigations, are summarized in Table 1. The Schmidt hammer test is a simple and quick procedure used to measure the rebund value of a calibrated mass on the discontinuity wall, which is useful to calculate the surface mechanical strength of the rock material in situ (Nazir et al., 2013) and to asses the weathering state both of crystalline (Gullà and Matano, 1997; Ietto et al., 2015) and of carbonate rock masses (e.g., Nasri et al., 2019). The Schmidt test was carried out according to A.S.T.M. (2001) recommendations. The average rebound values, collected for the most representative joint sets in the three measurement stations, range from 15 to 23. According to Nasri et al. (2019), these values show that the carbonate rock surfaces were affected by high weathering processes. Further qualitative estimations, based on visual observations of the wall material close to the discontinuity surfaces, allowed to classify the weathering state in the three measurement stations ranging between moderate and high. The joint spacing, ranging between 80 and 200 mm, results in the close spacing class. The roughness profile, that was defined on the basis of the classification scheme suggested by the I.S.R.M. (2014) and the related Joint Roughness Coefficient (JRC), was assigned on the basis of the scheme of Barton and Choubey (1977). The observed average profiles, acquired for the most representative joint sets, were classified as smooth undulating (JRC values 10–12) in all the measurement stations. The joint apertures, measured in the three stations, range between 0.7 mm (open class) and 0.5 mm (partly open class). The measurement of discontinuity trace lengths on the exposure surface (joint persistence), shows values ranging between 1-3m (low persistence class) and 3–10 m (medium persistence class). Finally, infilling material, formed of soft or consolidated material, was observed in almost all the fractures, with thickness less than 5 mm. Absence of water flow or free moisture (groundwater) was observed in all discontinuities.

The collected jointing features (Table 1) allowed to calculate the RMRb index through the classification scheme proposed by Bieniawski (1989). In this regard, the point load strength and the Rock Quality Designation (RQD) were defined, respectively, by laboratory test on several samples and by the Palmström (1982) method based on discontinuity number per m^2 of rock surface. The rating obtained for each parameter of the Bieniawski (1989) methodology and the final RMRb value achieved in each measurement station are shown in Table 2. The obtained RMRb values show a homogeneity of the rock mass quality in the three measurement stations, which falls in the III class (fair rock mass).

The RMRb values were employed in the classification scheme proposed by Romana (1985) in order to compute the SMR index. The latter provided an evaluation of the stability conditions of the studied rock slopes. The results are summarized in Table 2, showing that the examined portions of the escarpment fall in the IV (bad rock) and V (very bad rock) classes, which correspond to unstable and to completely unstable slopes, respectively. These values highlight a high failure probability, ranging from 0.6 to 0.9 (Table 2), meaning that the probability of failure is 90% and 60% respectively on the basis of Romana (1985) and Romana et al. (2015) classification schemes. Finally, the application of the GSI system (Hoek and Brown 1997) was used for the estimation of rock mass strength based on geological field observations. The achieved results showed equal values for the measurement stations 1 and 2, ranging between 40 and 45; the measurement station 3 highlighted a lower GSI value equal to 30-35 (Tab. 2). The lower GSI value at station 3 should be attributed to a slight change in the rock mass geomechanical condition compared to stations 1 and 2, as demonstrated by different RQD values (Tab. 1). Anyway, both GSI values fall in the same class showing fair surface quality of rock mass (Hoek and Brown 1997), characterized by smooth and moderately weathered surfaces that confirm the previous values collected during the geomechanical survey.

4.3 - Geophysical Survey

The Vp models obtained by seismic refraction method are shown as lineament 1 and lineament 2 in Figure 8. Both the models, performed in adjacent areas, reached an investigation depth of 20 m. The seismic models show a similar geomechanical condition of the underground rock mass in upper (lineament 1) and down (lineament 2) slope areas with respect to the scarp. Three layers were recognized with a gradual downward increase in Vp recorded in the model of lineament 1; while four layers were identified in Vp model of lineament 2 (Fig. 8). The gradual change in Vp, observed in both seismic models, should be related to a different fracturing degree of the carbonate rock mass (e.g., Miller, 1992; Guadagno and Nunziata, 1993), which decreases progressively with the depth. In particular, a shallow layer, with very low P wave velocities ranging from 350 m/s to 800 m/s, was recognized only in the seismic lineament 2 up to 5-8 m depth. A significant Vp value increase, ranging from 800 m/s to 1300 m/s, was observed in the same lineament 2 up to 13 m depth (layer 2) and as shallower layer in the seismic lineament 1 (layer 1). A progressive increase of Vp value ranging between 1300 and 1800 m/s marked the layers 3 and 2 in the seismic lineaments 2 and 1 respectively, denoting a lower fracturing state of the subsoil rock mass. Finally, higher Vp velocities characterize the deeper layers in both seismic lineaments, where Vp values greater than 1800 m/s were observed in the seismic lineament 2 at about 18 m depth (layer 4) and in lineament 1 at about 6-10 m depth (layer 3).

These values allowed to classificate the deeper horizons like rock masses with better mechanical properties and lower fracturing state. Finally, in the central part of both seismic models, the not planar setting of the layers is, probably, linked to two tectonic disturbances which cross the seismic traverses and are aligned to master fault NE-SW oriented.

4.4 – Extractions of geological planes

The UAV technology was employed to acquire images useful to the construction of a 3D model of the rock scarp (Fig. 9a). Subsequently, open-source CloudCompare software, through the FACETS plugin, was used to extract the geological planes on the whole rock escarpment. This process allowed to identify a number of facets equal to 11711 (Fig. 9b). Several gaps are present on facet model (Fig. 9b) due to the presence of vegetation, buildings, detritus and retaining wall, which cover the rock surface in some parts of the rock slope. The fast Marching (FM) method was employed to analyse the planar facets recognized on the whole rock surface. Subsequently, the different orientations of fracture sets were filtered with the ‘Stereogram’ plugin; so, a synthetic view of the obtained data is offered by the stereogram in Figure 9c. The recognized geological planes were grouped according to their dip/dip directions, so five major discontinuity sets were identified (Tab. 3) as follows: dip/dip direction for set 1 (green facets) is 75°±10°/125°±10°, for set 2 (orange-red facets) is 80°±10°/24°±9°, for set 3 (blue facets) is 60°±15°/210°±10°, for set 4 (purple facets) is 65°±10°/320°±10°, for set 5 (light green facets) is 75°±7°/68°±2°.

A detailed analysis of the planar facets was carried out on the escarpment portions where the three measurement stations, identified during the scanline survey, fall (Fig. 10a). In each measurement station, the selected escarpment rock surface was equal to 80 m^2. The FM method was employed to assess the main orientation of the geological planes enclosed in each escarpment rock area. Thus, 201 facets were identified in the station 1 (Fig. 10b), 478 facets in the station 2 (Fig. 10c) and 683 facets in the station 3 (Fig. 10d). In each measurement station the fracturation frequency was estimated, as well. The collected data point out that the station 3 is characterized by a higher fracturation frequency equal to 8.5 facets per m^2, the station 2 is marked by 5.9 facets per m^2, while the station 1 is characterized by the lowest jointing frequency with 2.5 facets per m^2. In each measurement station the FM methodology enabled to group the geological planes according to their dip/dip direction. Hence, in the measurement station 1 (Fig. 10b) the analysis of the extracted geological planes shows that there are four major discontinuity sets: the mean dip/dip direction for set 1 (green facets) is 82°/115°, for set 2 (orange-red facets) is 83°/22°, for set 3 (blue facets) is 55°/210° and for set 4 (purple facets) is 75°/323°. Also in the measurement station 2 (Fig. 10c) were identified four jointing sets as follow: set 1 (green facets) with 76°/128°; set 2 (orange-red facets) with 84°/30°; set 3 (blue facets) with 60°/215°; set 4 (purple facets) with 55°/310°. Finally, in the measurement station 3 (Fig. 10d) four major discontinuity sets were distinguished: set 1 (green facets) with 65°/133°; set 2 (orange-red facets) with 74°/19°; set 3 (light green facets) with 68°/80°; set 4 (purple facets) with 75°/315°. The recognized orientation planes (Tab. 3) are coherent with the jointing sets collected during field surveys (Tab.1), showing a difference of dip direction angle of about 10° between the data extracted from the CloudCompare software and scanline method. According to several authors (e.g., Tung et al., 2018; Nagendran et al., 2019; Kumar and Ismail, 2020) the approximation value of 10° can be considered within the tolerance limit. Once the soundness of the results between scanline and digital methodologies had been verified, the FM method was also employed in other 3 measurement stations (Fig.s 10, 10e 10f, 10g) in order to evaluate the fracturing state within portions of the rock scarp located in human inacessible areas. The examined surface was equal to 80 m^2 in each measurement station, hence 178, 254 and 728 facets were recognized in the 4, 5 and 6 measurement stations respectively. The recognized discontinuity sets were consistent with the previous ones and the fracturation frequency was equal to 2.2 facets per m^2 in the measurement station 4, wherease 3.1 and 9.1 were the frequency assessed in the measurement station 5 and 6.

5. - DISCUSSION

The research aims at studying the instability processes involving a rock escarpment located on the eastern side of the San Donato di Ninea village. In this area, several buildings and a portion of the municipal road are affected by frequent rockfall phenomena, which threaten the human safety. On the basis of geological, geomorphological, geomechanical and geophysical investigations coupled to drone survey, this study intends to provide a detailed and reliable reconstruction of the geological conditions of the rock scarp and to assess the slope stability state.

Field surveys showed that the studied escarpment is located close to an intersection of two tectonic lineaments responsible of a heavily fractured rock mass. According to many researchers (Brideau et al., 2009; Brunori et al., 2015; Barjasteh, 2019; Conforti and Ietto, 2019), in tectonized areas, the strong fracturation grade of the rock masses can be related to fault shear stress. Furthermore, the fault core along the zones of maximum shear, where cataclastic rocks occur, forms pre-existing lines of weakness, favouring both groundwater drainage and deep weathering processes (Jacobson et al. 2003; Liu et al. 2007). These processes give rise to a significant worsening of the mechanical properties, such as rock strength, favouring the slope instability (Dramis and Sorriso-Valvo 1994; Calcaterra and Parise 2010; Borrelli and Gullà 2017; Conforti and Ietto, 2019). In the studied area, rockfall phenomena occurr on the steep rock scarp, whereas, slide type instabilities dominate on the gentler slopes along the fault lineament NW-SE oriented. Therefore, in agreement with several authors (e.g., Brideau et al., 2009; Pedrazzini et al., 2011; Conforti and Ietto 2020) tectonic structures (faults and shear zones), slope topography and intense jointing state of the rock masses, seem to control the spatial distribution of landslides and the type of movement in the examined area.

The geomechanical investigations, carried out by using scanline method in three measurement stations located along the rock escarpment, showed that four joint sets were identified in each station. Furthermore, qualitative estimation and Schmidt hammer tests (e.g., Gullà and Matano, 1997) indicated that moderate or high weathering processes affect the rock masses involved in instability phenomena. The collected data allowed to classify the quality of rock mass using the Bieniawski (1989) methodology schema. The computed values point out that the quality of the rock falls in the III class (fair rock).

The application of the Romana (1985) classification provided an evaluation of the potential stability status of the rock slopes. The computed slope conditions range from unstable to completely unstable, corresponding to IV (bad rock) and to V (very bad rock) classes respectively. According to Romana (1985), the term “unstable” is used when planar failures in many joints or big wedges can occur; instead, “completely unstable” indicates that big planar failures or soil-like failures can be triggered on the scarps. These results were confirmed by the real stability conditions observed on the examined rock scarp, where worst contexts were identified close to the measurement stations 1 and 3. Indeed, in these areas, coincident with the bottom and the upper parts of the scarp (Fig. 3), many rockfall phenomena were triggered in the last decade. In particular, the last dangerous rockfall events are dated in April 2015, May 2016, November 2018 and January 2019. These instability events threatened the citizen safety requiring the road closure and urgent measures of hazard mitigation for the closest buildings.

The geological strength index (GSI) system was also computed for the estimation of the rock mass strength in all measurement stations. The GSI is widely used in visual examination of the rock mass exposed in surface excavations such as road cuts (Marinos et al., 2005). The obtained GSI values are consistent with those discussed in the GSI chart for tectonically disturbed rock masses (Marinos et al., 2005).

Several authors (e.g., Lee and De Freitas, 1990; Ietto et al., 2016) asserted that the seismic refraction prospecting is a suitable method to evaluate the mechanical properties in rock masses and to detect their progressive changing in subsoil. The increase in Vp values in subsoil usually corresponds an improvement of the mechanical and geotechnical properties of the rock mass, usually linked to lower jointing state and/or decrease in weathering state inside the rock masses (e.g., Guadagno and Nunziata, 1993; Palmstrom, 1996; Ietto et al. 2016). Therefore, two seismic refraction surveys were carried out at the top and bottom of the rock scarp in order to investigate the jointing change in subsoil. At this regard, it must be taken into account that the propagation of the seismic waves could be slightly affected by the topographic features of the slope. Indeed, a maximum amplification of the energy and velocity of the seismic waves usually occurs in the upper part of the hill (e.g., Jafarzadeh et al., 2015; Poursartip et al., 2017). For this reason, the second seismic refraction profile was performed at the foot of the studied rock scarp, in order to acquire the geomechanical changes with depth avoiding the possible topographic influences. In the studied area, the obtained seismic models are similar, showing a progressive increase of the P wave velocities with depth. In particular, a shallow layer, marked by very low P wave velocities, was observed only in the seismic lineament 2 located at the foot of the rock scarp where a surficial debris deposit is present. The gradual increase in Vp values with depth allowed to identify 3 additional seismic layers in both seismic models. Among these, the deepest layer, having Vp values greater than 1800 m/s, was found at about 6-10 m and at 18 m depth in the 1 and 2 seismic profiles respectively. The Vp values gradually increasing downward suggests a better quality of the rock mass with depth due to an increase in joint spacing and/or a decrease in joint aperture. Therefore, better geomechanical properties were found with depth and higher Vp values were achieved at 18-20 m depth; on the opposite, worst geomechanical conditions affect mainly the shallower part of the rock masses, from the surface up to a depth of 5-6 m. This condition suggests that the instability processes are limited within the shallower layers. Finally, both Vp models reveal the presence of faults that cross the seismic profiles as shown by the interruption of the tabular geometry of the recognized layers. These faults are associated with NE-SW striking fault lineament that, coupled to NW-SE fault system, are responsible of the high fracturing degree of the rock mass, as well as of the formation of weathered material enhancing the instability phenomena.

Geological, geomechanical and geophysical investigations, coupled to Beniawski and Romana classifications, allowed to evaluate the fracturation degree of the rock mass and its susceptibility to failure, but only in a limited area. In order to assess if the checked conditions can be considered as representative of the whole rock scarp, further geomechanical data were acquired by using an Unmanned Aerial Vehicles (UAVs). In the last decades, the coupling of UAV technique with optical cameras, have been employed in recognition, mapping, monitoring and hazard analysis of the instability processes (e.g., Rossi et a., 2018). Thus, an overview of the geomechanical conditions on the whole studied escarpment was obtained by high-resolution images collected through an UAV. The acquired images, subsequently, allowed the construction of a 3D model of the studied rock scarp (Fig. 9a). At this regard, according to the recent international scientific literature (Tung et al., 2018; Gupta and Shukla 2018; Nagendran et al., 2019), the FACETS plugin in CloudCompare software was employed to extract the geological planes and the discontinuity sets from the 3D model of the rock escarpment. Thus, six measurement stations were analysed by digital methodology; in particular, three measurement stations corresponding to the ones used during the scanline survey and three other ones were chosen along human-inaccessible areas to increase the investigation area and to verify the possible change in the fracturing state. In the first three stations, the joint sets, identified by digital methodology and scanline in-situ method, are similar with only a slight difference of about 10° in the dip direction angle. Furthermore, the digital methodology allowed to evaluate the fracturation frequency within the six analysed areas, revealing that the inaccessible station 6 is the most fractured area. Thus, in the last one and in the station 3 also characterized by a high jointing state, the possibility of rockfall, involving small rock blocks, is very high. Viceversa, in the other stations, as the joint frequency is lower, rockfalls or wedge failures can be larger in size. Hence, the use of the low-cost UAV technology, digital photogrammetric technique and CloudCompare software, represents a useful tool able to provide reliable results that increase the geomechanical information on large area with respect to the scanline method, and also supplying data in human inaccessible areas such as the upper part of the rock scarp. Obviously, the quality of data required for the extraction of geological planes is strongly dependent on the density of the point cloud produced. The collected results testify that the FACETS alghorithm can be very easily employed for the recognition and control of the geomechanical features in wide areas, as well as it can be used as a valid support of landslide management in impervious environment and inaccessible areas. Anyway, in our opinion, the geomechanical field investigation represents always a reliable and accurate approach and the CloudCompare method can provide useful additional geomechanical information on investigated area, but it does not substitute the fieldwork. Indeed, the data collected only through field investigations, such as by scanline method, might be not representative of the geomechanical conditions of the whole studied area, because such investigations only concern a limited rock volume, which is moreover usually located at the bottom of the scarp where the human accessibility is facilitated. Instead, joint orientations and frequency can change in unaccessible zones between the bottom and the upper part of the rock slope.

The present research testifies the importance and the great potential of the combined use of different approaches able to reach satisfying results in the study of geomechanical conditions and instability processes on rock scarp. Indeed, the use of different methods allowed to obtain an exhaustive and detailed characterization of the geomechanical conditions on the whole rock escarpment. In particular, the scanline method, used in three measurement stations, provided a careful collection of the discontinuity features useful both to the assessment of the rock quality and to the evaluation of stability conditions on the three portions of the rock scarp through Bieniawski, 1989 (RMRb index), Romana,1985 (SMR index) and Hoeck and Brown, 1997 (GSI system) classification schemes. In order to investigate on subsoil mechanical properties of the rock mass and their variations with depth, two seismic investigations were performed. The further investigation through the UAV technology enabled the construction of a 3D model of the escarpment; the successive use of Cloudcompare software allowed to recognize the geological planes and the discontinuity sets on the whole rock scarp. The collected digital data had an appreciable validation with the field data, providing a complete geomechanical characterization of the whole rock slope, overcoming the limit of the use of only field investigations performed in limited human accessible areas. The procedure of the flow-chart of Figure 2, more generally, could be useful also in different contexts to investigate similar morphodynamic processes.

6. - CONCLUDING COMMENTS

The studied area focuses on a rock scarp in the San Donato di Ninea village (Cosenza Province) located in the northern sector of the Calabria Arc (south Italy). The rock scarp is constituted by a carbonate succession, intensely tectonized and jointed, involved in widespread rockfall phenomena. Geomechanical data, collected through the scanline method in three measurement stations, allowed to compute the RMRb (Bieniawski,1989) and SMR (Romana, 1985, 2015) indexes. The results showed that the Rock Mass Quality falls in class III for RMR classification, and the scarp stability ranges between unstable and completely unstable, corresponding to IV (bad rock) and V (very bad rock) classes for Romana classification. The discrepancy of attribution class, between the two used classification appoaches (Bieniawski, 1989; Romana, 1985), occurs because RMRb system originally was developed by Bieniawski for the estimation of rock mass properties in underground excavation; instead, SMR classification (Romana, 1985) is a correction of the previous basic RMR in order to adapt it for the slope stability evaluation using three correction factors. Geophysical investigations showed that the worst geomechanical properties affect mainly the shallower portion of the rock masses, up to a depth of 5-6 m. The scanline method can be used only in human accessible areas of the rock scarp, so, additional geomechanical information on the whole escarpment were acquired by high-resolution images obtained through a drone. The comparison of the results achieved by scanline and digital methodologies showed similar joint sets; moreover, digital analysis of joint systems allowed to investigate also inaccessible areas where a higher fracturation frequency was found. Such integrated geomechanical characterization could be useful mainly to local authorities to improve the assessment of the hazard condition and the management of the mitigation strategies at large extents. It can be stated that the UAV technique and related digital softwares showed a good precision, though an improvement of the softwares for collection, management and processing of geomechanical data is needed.

Finally, it should be highlighted that low-cost UAV investigations and digital photogrammetric techniques should not replace field investigations. Rather, they should be employed as complementary investigation methodology to enhance the geological information and the assessment of the slope stability in human inaccessible areas, testifing the great importance to employ a multi-approach for the study of rock slope.

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Features	Station 1	Station 2	Station 3
Slope face (dip/dip direction)	80°/54°	66°/346°	76°/60°
number of discontinuity	177	93	257
Joint set 1 (dip/dip direction)	80°/120°	55°/320°	65°/330°
Joint set 2 (dip/dip direction)	70°/15°	80°/20°	80°/20°
Joint set 3 (dip/dip direction)	45°/220°	50°/200°	70°/65°
Joint set 4 (dip/dip direction)	75°/330°	80°/120°	70°/135°
Schmidt Hammer test (average value)	23	20	15
Strength of intact rock material (Point Load Test in kg/cm^2)	51.90	58.70	64.24
RQD by Palmström (1982)	42	35	20
discontinuity spacing (mm)	80 Close spacing	200 Close spacing	200 Close spacing
trace length (m)	Low persistance (1-3)	Medium persistance (3-10)	Medium persistance (3-10)
Joint aperture (mm)	Open (0.7)	Partly open (0.5)	Partly open (0.5)
Joint roughness (coefficient JRC*)	Smooth, undulating (10–12)	Smooth, undulating (10–12)	Smooth, undulating (10–12)
Weathering	Higly weathered	Moderately weathered	Moderately weathered
Infilling (mm)	Soft (<5)	Consolidated (<5)	Consolidated (<5)
Groundwater	Absent	Absent	Absent

Tab. 1 - Mechanical conditions and orientation (dip/dip directions) of the discontinuity sets identified from measurements in the 3 stations; *JRC: Joint Roughness Coefficient in Barton and Choubey (1977).

		Station 1	Station 2	Station 3
Strength of intact rock material		12	12	12
RQD		8	8	3
discontinuity spacing		8	8	8
Conditions of discontinuities	trace length	4	2	2
	Aperture	4	4	4
	Roughness	3	3	3
	Weathering	1	3	3
	Infilling	2	4	4
Hydraulic condition		15	15	15
Basic RMR		57	59	54
Class		III (Fair rock)	III (Fair rock)	III (Fair rock)
Romana (1985) RMR+(F1xF2xF3)		RMR -51	RMR -20.4	RMR -35
SMR		6	38.6	19
Class		V (very bad rock)	IV (bad rock)	V (very bad rock)
Slope condition		Completely unstable	Unstable	Completely unstable
Failure probability		0.9	0.6	0.9
Geological strength index (GSI, in Hoek and Brown, 1997)		40-45	40-45	30-35

Tab. 2 – Bieniawski (Basic RMR), Romana (SMR) and GSI classification methods calculated in the three measurement stations.

Joint sets	Entire rock scarp	Station 1	Station 2	Station 3
1 (dip/dip direction)	75°±10°/125°±10°	82°/115°	76°/128°	65°/133°
2 (dip/dip direction)	80°±10°/24°±9°	83°/22°	84°/30°	74°/19°
3 (dip/dip direction)	60°±15°/210°±10°	55°/210°	60°/215°	68°/80°
4 (dip/dip direction)	65°±10°/320°±10°	75°/323°	55°/310°	75°/315°
5 (dip/dip direction)	75°±7°/68°±2°.			

Tab.3 – Discontinuities extracted digitally through the CloudCompare software (for the location of the stations, see Fig. 10)

Figure captions:

Fig. 1a and 1b) Geographic location of the studied area; 1b Structural framework of the studied area (east dipping fault in red and west dipping fault in blue by Brozzetti et al. 2017): 1 and 2 points show the Sangineto-San Sosti and San Sosti-Saracena tectonic lineaments respectively; 1c geological map of the studied area; 1d NE-SW geological cross-section (for the location, see 1c).

Fig. 2 - Flowchart of the used approach

Fig. 3 – Location of the geological field investigations.

Fig. 4 – Scheme of photos acquired by UAV: a) Blue points show the photos taken in the studied area; 4b) Density map showing the number of overlapping photos acquired by drone investigation on the basis of the scheme of photos showed in 4a; 4c) Ground Control Points (GCP) Markers; 4d) Ground Control Points chosen for a better georeferencing of the aerial photogrammetry (image from drone).

Fig. 5 – Landslides map and slope gradient map of the studied area.

Fig. 6 – Examples of high hazard conditions: the yellow arrows indicate the unstable rock masses on the studied scarp.

Fig. 7– Photos pole and great circles Schmidt stereonets, where the main discontinuity sets found in the three measurement stations are plotted. The joint sets are displayed in the lower-hemisphere Schmidt stereonets. Location of the stations are shown in Fig. 3; joint set data and features for each measurement station are shown in Table 1.

Fig. 8 – Geophysical surveys performed in the studied area (see Fig.3 for the location). The red dotted lines show the fault lineaments.

Fig. 9a – 3D Model of the studied rock scarp; 9b - facets extracted from 3D dense cloud using FACET plugin in CloudCompare; 9c - stereogram of facets of the whole rock scarp (front view) produced in CloudCompare

Fig. 10 – 10a) Dense Cloud Model of the studied rock slope, blue colour on the rock slope shows the areas covered by vegetation and buildings; 10b, 10c, 10d, 10e, 10f, 10g) facets extracted in the six measurement stations (front view) from 3D dense cloud using FACETS plugin in CloudCompare. Yellow labels show the measurement stations employed for scanline and digital methodologies; red labels point out the measurement stations used only for digital method.

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