Laser Scanning Applications for Monitoring Tuffaceous Coastal Cliff in the Pozzuoli Bay, Punta Epitaffio Site, Italy: preliminary results

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from remote sensing to 3D geological modelling

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1. Introduction - Campi Flegrei is one of highest volcanic risk areas of the world, with a population of more than 300,000 inhabitants and relevant infra-structures. Its coastal zone is prone to both natural and anthropogenic hazards, including earthquakes, tsunamis, ground deformation, landslides, floods, storm surges, coastal erosion (BENEDUCE et al., 1988; LIRER et al., 2001). The study presents a Terrestrial Laser Scanning application for landslides monitoring in the coastal zone of the Pozzuoli Bay (Campi Flegrei area, figure 1). As a matter of fact, TLS has been successfully used to monitor landslide phenomena over wide areas and with a high level of detail (ABELLAN et al., 2011; 2010; FANTI et al., 2013; NGUYEN et al., 2011).
TLS based monitoring of the tuffaceous cliffs of the Pozzuoli Bay is of primary interest for the understanding of morphogenetic processes associated with the evolution of the coastal zone and provides the necessary integration to Civil Protection authorities for the assessment of the full spectrum of natural hazards in a volcanically active area.

2. Geomorphological settings - The coastal zone of the Pozzuoli Bay is represented by rocky cliffs with minor sandy beach segments. Coastal cliffs mostly consist of welded pyroclastites, tuffs and ignimbrites. These coherent but relatively erodible volcaniclastic rocks are considerably prone to weathering in marine coastal environment and may be subject to extremely fast erosion over relatively short time periods. Coastal cliffs are also characterized by rapid evolution by landslide processes, with abrupt changes in the shape of the slope and the seafloor morphology at the toe of the cliffs. The most effective processes in the shaping of coastal morphology are landsides in general, including mechanisms classified as rock fall, rock topple and rock slide (CRUDEN & VARNES, 1996).
Based on an inventory of the coastal tuffaceous cliffs of the Pozzuoli bay, a number of sites particularly exposed to hydrogeological risk have been identified (figure 1). The selection has been made in order to include a spectrum of factors that are relevant for multi-hazard assessment, including the slope morphology, the exposure of coastal cliffs to marine erosion, the type of geological substratum and the anthropogenic pressure.

3. Geology of Punta Epitaffio site - The coastal cliff of Punta Epitaffio, located near Bacoli city (figure 2), has been selected as the test site for the TLS survey of the coastal zone of the Pozzuoli Bay, as representative of a tuffaceous coastal cliff in a densely populated area.
The Punta Epitaffio cliff is characterized by the outcrop of the "Mofete or Epitaffio Yellow Tuff" formation, a lithified ignimbritic deposit dated between 10,7 and 15,3 ka BP (LIRER et al., 2011). It is represented by welded thinly bedded pyroclastic deposits, made up of white vescicular pumice lenses within a yellowish sand-ashy matrix. The exposed succession is characterised at the top by ca. 10 m thick loose pyroclastic and colluvial deposits.
The selected cliff is about 50 m high and 400 m wide; it is exposed to east and is crossed halfway by a country road (figure 2). The studied central sector of the cliff is 30 m high and 60 m wide (figure 3) and is the only not reinforced segment of the slope; the southern and northern sectors have been reinforced by shotcrete, wire mesh and steel cable network applied to the tuff wall, realized in the last years after a series of rock falls occurred up to 2010.
The road has been often closed to traffic over the last decades. Interruptions have been mostly caused by rock falls from the upper part of the slope and local collapse of the roadway due to progressive erosion and retreat of the lower part of the slope subsequent to marine erosion at the base of the cliff. The last collapse of blocks of tuff occurred on January 22 after heavy rains (figure 4).

4. Laser scanning survey
A long-range terrestrial laser scanner RIEGL VZ1000® equipped with a 14 megapixel external digital camera was utilized for data acquisition. During the survey, each fixed station has been programmed for twofold scanning of rock surfaces ca. 30 m high and 60 m wide. All measurements have been referred to UTM coordinate system (datum WGS84). The main output of the acquisition phase is a 3-D point cloud and RGB images of the test area (figures 5 and 6). Raw data files have been then processed using RiScanPro® software on Ar-cGIS® platform.
The workflow of data acquisition included the following main steps: 1) Preliminary data acquisition and site inspection; 2) Topographic survey for georeferencing TLS data; 3) Laser scanning from fixed scan positions; 4) Data pre-processing (point cloud analysis and filtering, noise removal, filtering vegetation, scan registration); 5) georeferencing in the UTM coordinate system (datum WGS84).

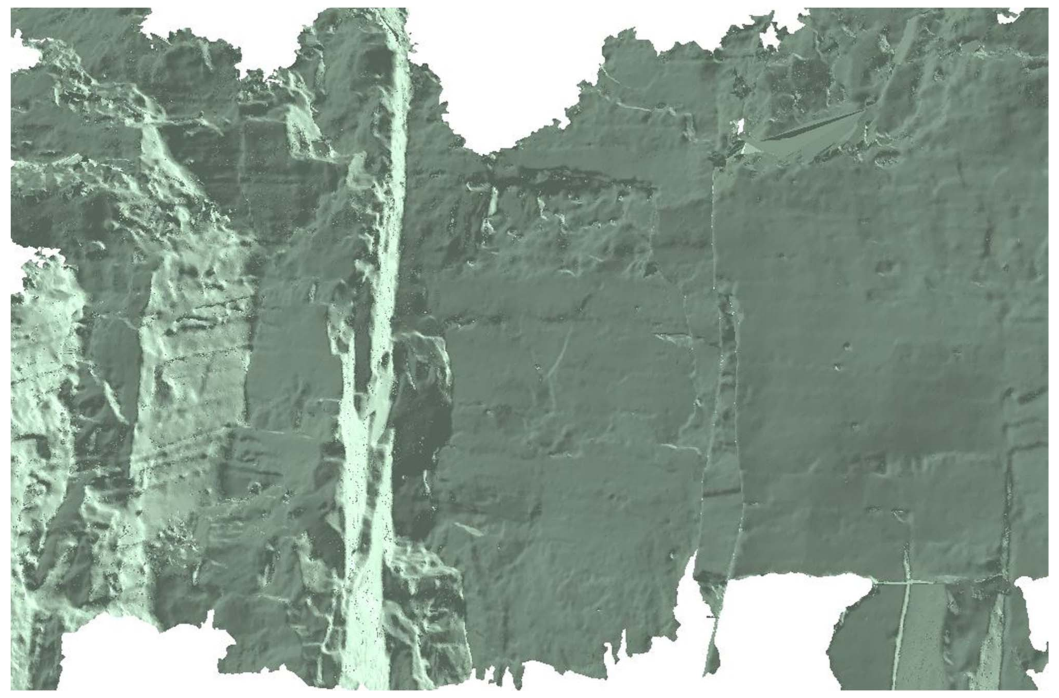

Figure 7 - 3-D model (triangular mesh) of Punta Epitaffio tuffaceous cliff

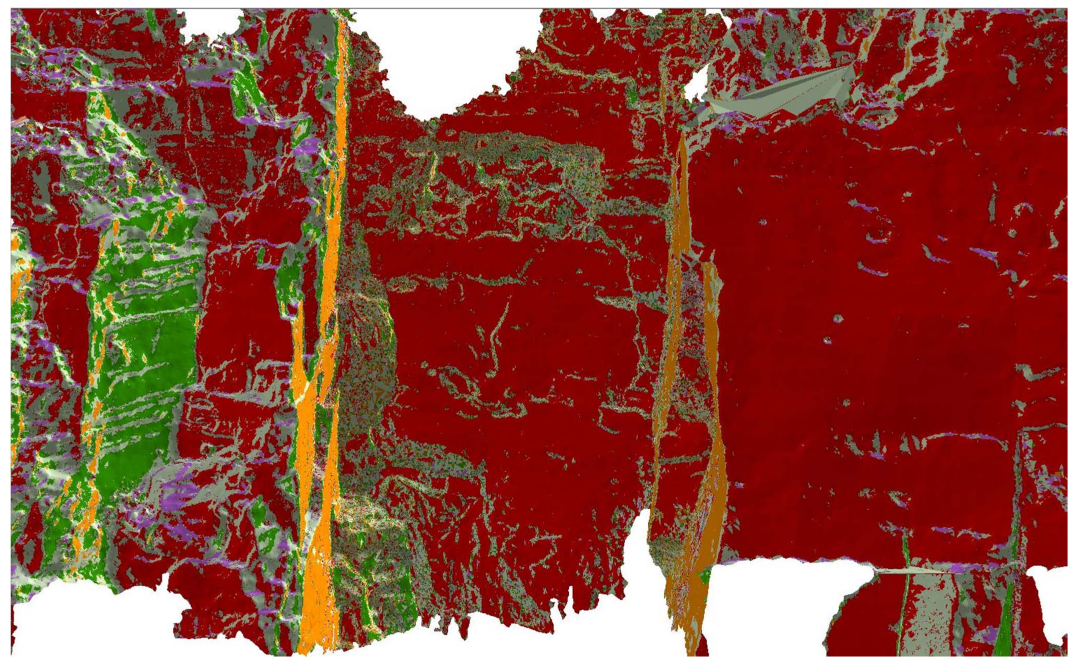

Figure 9 - Structural discontinuity sets overlapped to the 3-D mesh through a GIS software (K1 set - orange, K2 set - red, K3 set - green)

5. Data processing and analysis
The survey method adopted allowed to obtain a high-resolution digital 3-D model of the cliff with a cell dimension of less than 5 cm. The acquired point cloud was used to build a georeferenced DTM of Punta Epitaffio cliff.
The workflow of processing steps applied to the laser scanner data includes: 1) laser data modeling; 2) interpolation of 3D discrete data in a continuous grid (raster and TIN); 3) extrapolation of spatial data to be used on GIS platforms ; 4) analysis of 3-D model in GIS environment; 5) development of vertical cartography (topographic maps); 6) development of vertical geo-structural maps; 7) integration and comparison with external data in GIS environment; 8) development of thematic maps.
The integrated analysis of the results of the laser survey has produced a high-resolution 3-D model (triangular mesh) of Punta Epitaffio tuffaceous cliff (figure 7). The numerical integration of slope angles and orientation of the topographic surface was used to obtain a 3-D digital model constituted by triangular mesh, where each element is associated with its spatial attitude (strike and dip angle).
The cliff morphology has been represented as a digital model of the preferential spatial orientation of planar-like surfaces exposed on the rock surface, and correlated with families of discontinuities within the rock (e.g. fractures, faults planes, bedding or morphological surfaces, etc.) according to classes of orientation (dip and dip direction).
A geostatistical analysis of rock discontinuity surfaces extracted from the triangular mesh (figure 8) identified three main sub-vertical joint sets that are sub-orthogonal to the cliff:
1) K1 (dip direction 135°/165° and 315°/345°, dip >75°);
2) K2 (dip dir. 245°/275° and 65°/95°, dip >70°);
3) K3 (dip dir. 180°/210° and 0°/30°, dip >70°).
The analysis of structural discontinuities on the 3D model shows a remarkable correlation between the virtual discontinuities of the rock detected from laser scanning and the families of fractures and faults (figure 9) actually measured in the outcrop by classic geo-structural analysis. A series of spatial queries allowed us to show the overlapping between the 3D model, the current discontinuity surfaces and the geological features of the different sectors of the cliff (figure 9).
In order to detect instability conditions and to identify areas susceptible to different types of collapse, a preliminary kinematic analysis has been performed by combining discontinuity dip and dip directions with local slope orientations, in order to individuate unstable tuff wedges and planar surfaces, predisposing the cliff to rock falls and rock topples. The analysis is still in progress.

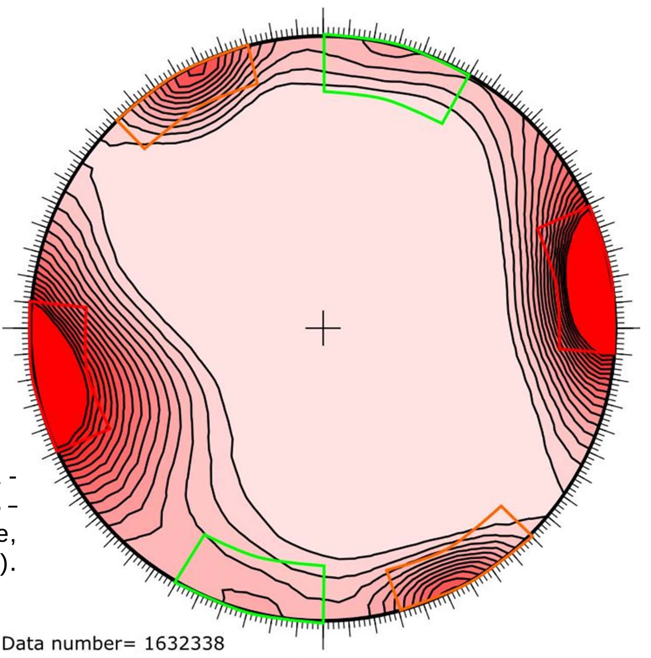

Figure 8a - Density diagram (K1 - orange box, K2 - red box, K3 - green box) (OpenPlot software, Tavani et al., 2011).

Data number= 1632338
Min value= 0.25 Increment= 0.25

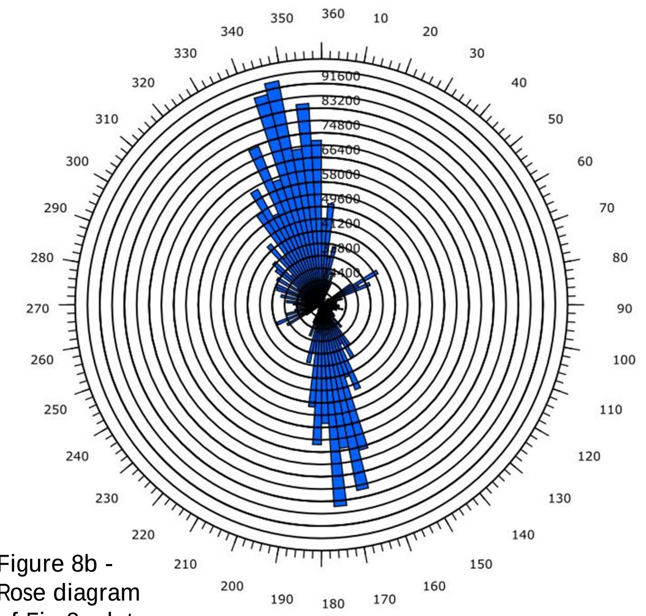

Figure 8b - Rose diagram of Fig.8a data.

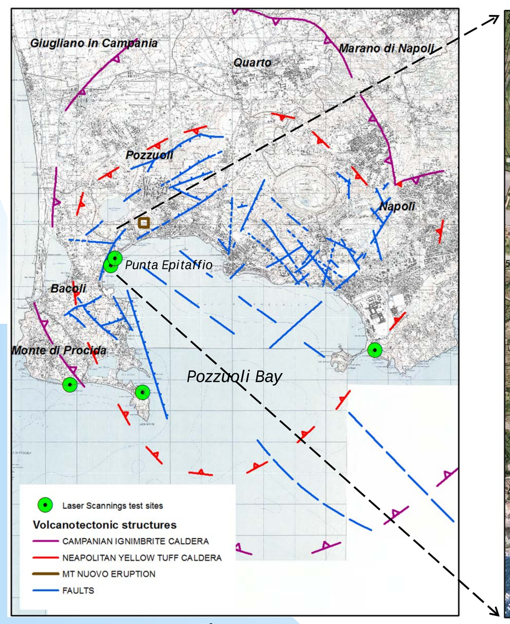

Figure 1

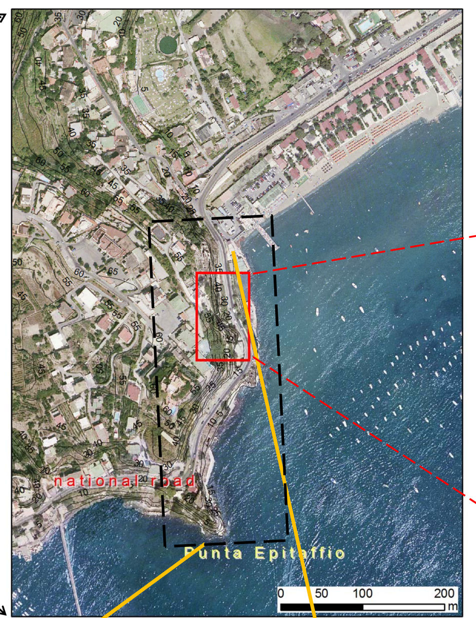

Figure 2

Figure 3

Figure 6 - True color scan of the box area in Fig. 3

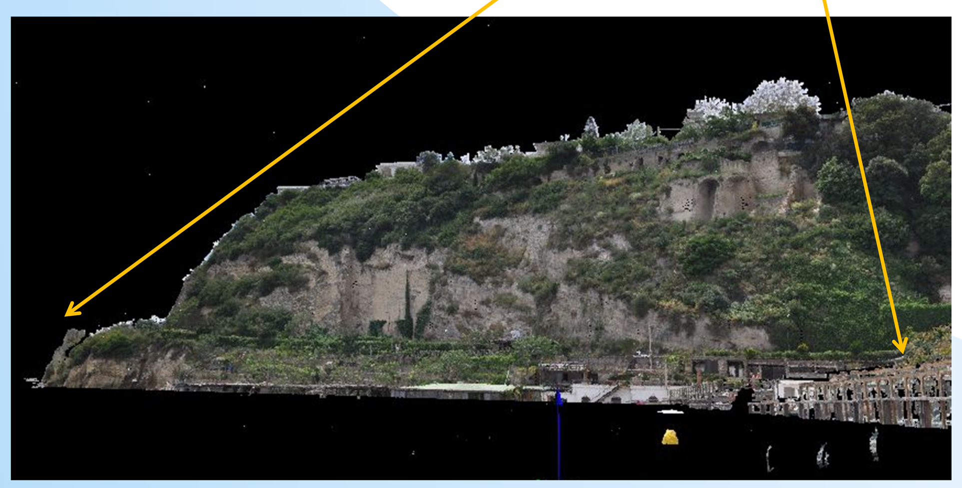

Figure 5 - True color scan of the box area in Fig. 2

Figure 4 - Falls of small tuff blocks on 22 Jan, 2014

6. Preliminary conclusions
The main goal of this research is the detection of unstable areas along the cliffs, the understanding of landslide mechanisms and the quantitative estimate of the rock volumes potentially involved by landslides phenomena. The TLS test conducted at Punta Epitaffio site was designed to implement landslide monitoring in highly urbanised areas such as the Campi Flegrei, near Napoli town (Italy). According to the results obtained from this research, a number of preliminary conclusions can be drawn as follows:
(1) TLS is a remote sensing technique providing a complete, dense and very accurate dataset for large survey areas.
(2) With respect to standard topographic monitoring, generally used to evaluate the displacement of individual significant points within a slope, the TLS monitoring method provides information on the stability (in terms of volumetric changes) over large slopes, therefore it offers a robust dataset for exhaustive geomorphological analysis of a given area.
(3) TLS monitoring data processed with a GIS-based platform offer the opportunity to realize thematic maps from integration with other georeferenced layers of information, through the development of simple query system.
In order to obtain a full assessment of the susceptibility to landslide phenomena of a given area, the TLS method needs integration with other relevant data, to be acquired by fieldwork investigation, e.g. mechanical properties of the rock, geostructural characterization of the bedrock, soil cover type, water content, etc. Nevertheless, this method has proven to be the most effective to develop quantitative morphometric analysis and monitor landslide evolution over regions exposed to high risk.
The TLS acquired dataset also represents an archive database for constraining the study of the evolution of the rock mass morphology after future TLS campaigns.
The accuracy and reliability TLS technique adopted in this study suggests that this methodology can be successfully used as complementary to the standard monitoring conducted with geodetic side-angle measurements.
The results of this study represent a first step in the progress of the research project "MONICA" (Innovative Monitoring for the Coasts and the Marine Environment) dedicated to multirisk monitoring and the realization of an early warning system for the Campi Flegrei – Pozzuoli Bay area on the basis of innovative integrated technology including optic fiber devices and networks.

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