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Application of an integrated monitoring system for rock failures in the Coroglio tuff cliff (Naples, Italy)

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ABSTRACT: In high risk, coastal, urban areas, cliff stability monitoring is an essential task for human activities. This paper presents the implementation of an integrated monitoring system at the Coroglio tuff cliff, located in the highly urbanized coastal area of Naples (Italy) on the border of the active volcanic caldera of Campi Flegrei. The system consists of standard geotechnical monitoring instruments (crack-meters and clinometers) coupled with a modern deformation monitoring technique based on Brillouin Optical Time-Domain Analysis (BOTDA) optical fiber network, integrated by a velocimetry sensor and a weather station. Remote sensing equipment like UAV digital photogrammetry (UAV-DP) and terrestrial laser scanning (TLS) have been also used for obtaining detailed multitemporal DTM of the cliff, as well as geostructural analysis and classification of the slope, supported by structural fieldwork. In the first phase of the study, we integrated the results of long-range TLS surveys with structural field mapping. The accurate and rapid detection of structural discontinuities of the rock played an important role for the understanding of the failure mechanism and the kinematic analysis of unstable blocks along the cliff. The preliminary results obtained during the first two year of monitoring activity (2014–2015) are presented. Micro-deformation of rocks measured by geotechnical sensors reveals a general sinusoidal trend, possibly linked to the bulk volume variation of the rocks, as a response to seasonal and daily temperature variations. This research provides a contribute to the understanding of the rates of geomorphic evolution of coastal tuff cliff and its relation with forcing factors (e.g. meteo-marine weathering, human actions, volcano-tectonic activity) in the perspective of early-warning actions and policies.

1 INTRODUCTION

The use of monitoring systems is becoming a standard practice to assess and predict geological hazards, as rock failures along slopes, and correctly plan future mitigation activities (Salvini et al., 2015).

Slope stability studies and monitoring may result unpractical in specific cases, such as tall cliffs. The deployment of an adequately planned monitoring system is often complicated for the lack of a adequate knowledge of local geological conditions for the difficulty or even impossibility of a direct survey. Indeed, there are different types of monitoring systems for rock failures, characterized by various levels of accuracy, invasiveness, distance range, integration and cost, that are applicable depending on several physical and human factors.

The use of remote sensing techniques like terrestrial and UAV Digital Photogrammetry (DP), Terrestrial Laser Scanning (TLS), ground-based Interferometric Synthetic Aperture Radar (InSAR), integrated with topographic instruments, such as Global Positioning System (GPS) and total station, provides a necessary geo-structural basis for designing and installing appropriate monitoring systems.

The present paper describes the implementation of an integrated system aimed at the monitoring of a number of physical parameters controlling the rock slope stability. The system has been installed on the the Coroglio tuff cliff, located in the highly urbanized coastal area of Naples (Italy), on the border of the active caldera of Campi Flegrei (Figs. 1 and 2).

The study combines engineering, geological and geostructural surveys conducted on selected areas by climber geologists, in combination with remote sensing techniques (TLS) on inaccessible areas. The integrated monitoring system is formed by three main components, including: a) TLS multi-temporal scans since April 2013; b) a meteorological station operative since January 2013; c) a combined geotechnical and seismic system operative since December 2014. These components have been integrated by an optical fiber sensing network since May 2015.

The preliminary results obtained during the first two years of activity (2014–2015) are also discussed.

The proposed research is a contribute to the understanding of the geomorphologic evolution of a coastal tuff cliff in a volcanically active area and its relation with forcing factors (e.g. weather and marine weathering, human actions, volcano-tectonic activity) in the perspective of early-warning actions and policies.

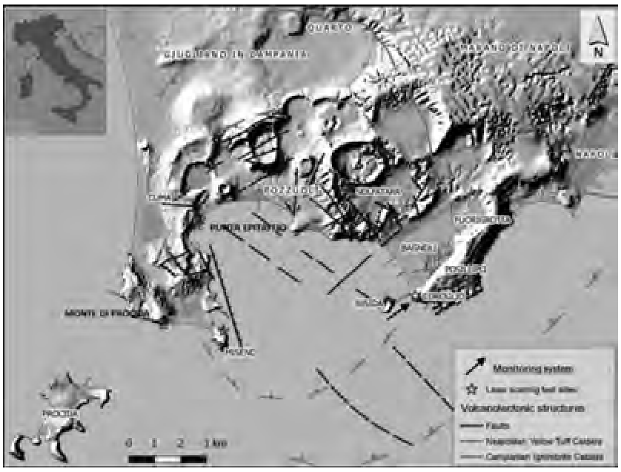

Figure 1. Study area and monitoring system location.

Figure 2. Coroglio cliff view from Nisida island.

2 GEOGRAPHICAL AND GEOLOGICAL SETTING

The Coroglio cliff is ca. 140 m high and 250 m wide, and is exposed towards the SW (Fig. 1 and 2). The cliff includes several rock fronts that may exceed 50 m in height.

Due to the general instability conditions of the cliff in the last decades, and after a major rock fall that occurred in 1990, the upper part of the northern sector of the tuff cliff has been subject to reinforcement works, consisting in steel bars anchored and bolted to the rock and a wire mesh and steel cable network applied to the tuff wall. At the foot of the cliff there is a sandy beach, particularly popular during the summer period.

The uppermost part of the exposed succession is characterized by a ca. 30 m thick loose pyroclastic deposits (Fig. 3). The rocks exposed on the cliff are represented by the upper member of the "Neapolitan Yellow Tuff" formation, a lithified ignimbritic deposit dated at ca. 15 ka BP.

The stratigraphic succession is formed by alternating coarse-grained, matrix-supported breccia, thin-laminated lapilli beds and massive ash layers. The deposit overlies the older tuff cone of Trentaremi (dated ca. 22.3 ka BP), consisting of partly welded to welded, whitish-yellow, coarse-grained, pumiceous fragments in a sandy ash matrix and lapilli beds. At the base of the cliff (Fig. 3), slope talus breccia and beach deposit also occur. The upper part of the cliff has been reinforced during the last 15 years after a series rock falls occurred between 1985 and 1990. Consolidation works consisted in steel bars anchored and bolted to the rock, along with wire mesh and steel cable network applied to the tuff wall.

The volcaniclastic succession cropping out at the Coroglio cliff is characterized by a complex system of mostly steep and planar structural discontinuities and

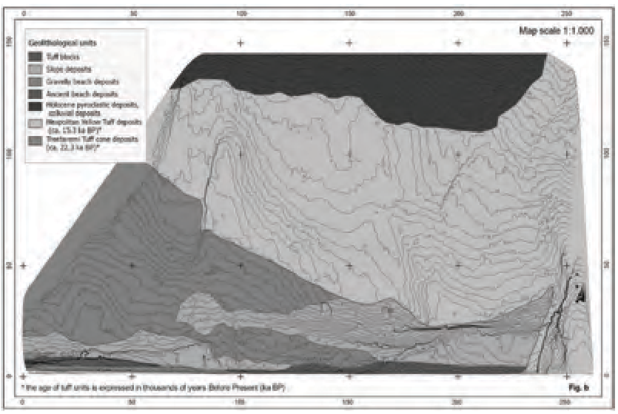

Figure 3. Geological map of Coroglio cliff (Matano et al., 2015). Contour lines interval is 0.25 m.

fractures (Matano et al., 2015) showing highly variable spacing, well-developed NE–SW and NW–SE directions, and subordinate NS and EW trends.

3 METHODOLOGICAL APPROACH

Cliff failures can have multiple predisposing factors, often depending on lithology, weathering and fracturing conditions, local natural environment (e.g, high mountain, cliffed coasts) and exposure.

Several experimental monitoring systems are operative in mountain environments, such as in Swiss Alps (Spillmann et al., 2007) and Northern Apennines (Salvini et al., 2015). These systems have the purpose of detecting and measuring the small ground deformations that can be regarded as precursors of rock ruptures.

Different types of sensors, such as accelerometers, crackmeters, clinometres, extensometrs and piezometres are employed together with communication systems able to operate in wild natural settings, which are often characterized by extreme weather conditions and limited accessibility. These geotechnical sensors can be assembled into integrated systems to monitor physical properties of rocks and environmental parameters, like surface temperature and humidity, which may induce volumetric variations leading to slope instability.

Methodological approach followed in this study consists in the following stepwise procedure:

1. Inventory of the slope instability processes involving the cliff and analysis of their historical evolution;
2. Slope stability analysis based on geomorphologic, geo-structural and topographic surveys;
3. Planning of monitoring network system and selection of appropriate sensors, acquisition devices, communication systems and softwares;
4. Installation and testing of the integrated monitoring system, definition of thresholds, sampling rates and time intervals during data acquisition;
5. Management of the monitoring system, data storage and validation of measurements;
6. Maintenance of the monitoring systems.

4 TOPOGRAPHIC AND GEO-STRUCTURAL SURVEYS

Detailed topographic and geostructural surveys were carried out on the Coroglio cliff, as reported in Matano et al. (2015) and Sacchi et al. (2015).

Instruments used in data acquisition were: (i) Leica TS12 3” R1000 Total station; (ii) Riegl laser scanner VZ1000 equipped with a Nikon D90 digital camera; (iii) GNSS Leica Viva GS08plus.

During the first phase of the study, we integrated the results of long-range TLS surveys (Fig. 4) with structural field mapping. The accurate detection of structural discontinuities of rock plays an important role for kinematic analysis of unstable blocks along the cliff surface and the understanding of the failure mechanism, and for the failure susceptibility definition. The geostructural survey allowed to obtain several results.

The main achievements are:

- Spatial orientation of the most significant discontinuity surfaces on the cliff and characterization of the rock mass fracturing conditions;
- Identification of unstable tuff blocks on the cliff and determination of the critical conditions for the installation of the monitoring sensors;
- Structural characterization of the discontinuity surfaces that isolate unstable blocks;
- Identification of the slope failure mechanisms.

According with the results of the geo-structural studies of Matano et al. (2015) and Froldi (2000), six sets of structural discontinuities were identified. The dip and dip direction ranges of defined sets are:

- F1: 35–65° and 220–255°;
- F2: 0–30° and 180–220°;
- F3: 60–110° and 255–280°;
- F4: 110–180° and 300–355°;
- F5: 50–195° with dip 20–65°;
- F6: dip < 20°.

The sets were mapped in a GIS environment using the digital elevation model obtained ty the TLS surveys (Matano et al., 2015).

Remote sensing equipment, like terrestrial laser scanning (TLS), has been used to address geostructural analysis and obtain a classification of the slope, supported by structural fieldwork, as well as detailed multitemporal DTMs of the cliff (Caputo et al., 2015).

Figure 4. Point cloud derived by TLS survey of Coroglio cliff.

5 MONITORING SYSTEMS

The monitoring system consists of standard geotechnical monitoring instruments (crackmeters and clinometers) integrated by an optical fiber network based on Brillouin Optical Time-Domain Analysis (BOTDA) and a velocimetry sensor (Fig. 5).

The various sensors of the system can measure:

- Meteorological parameters: Air Temperature, Humidity, Wind, Atmospheric Pressure (Barometer), Rain;
- Opening variations in rock fractures;
- Slope angle variations of rock surfaces;
- Rock temperature.

A weather station (Fig. 6) equipped with thermometer, barometer, hygrometer, anemometer and rain gage, was also installed in the vicinity of the Coroglio cliff.

5.1 *Geotechnical system*

More in detail, 9 monoaxial mechanical crackmeters, 2 biaxial clinometers, 2 thermometers and 1 velocimeter have been installed on selected unstable tuff blocks. Continuous data recording of geotechnical sensors is active since December 2014. The system presently acquires 48 daily measurements, i.e. one every 30 minutes.

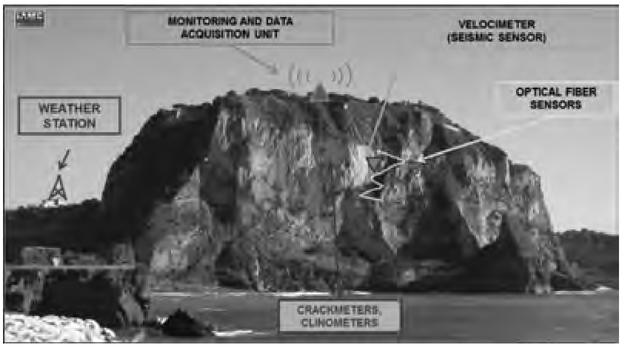

Figure 5. Perspective view of Coroglio cliff with location of monitoring network.

Monitoring of unstable blocks (Fig. 7) is performed through specific extensometers that measure the linear opening of isolating fractures, and inclinometers that detect spatial attitude modification due to rotation of tuff blocks. All instruments were installed on the cliff by climber geologists. Each sensor is protected from direct solar radiations and connected to the main acquisition system by a cable network fixed along the rock surface.

The wired network is made of special cables reinforced with a rigid plastic sheath, all the way from the monitoring sites to the data acquisition units at the top of the cliff.

The obtained dataset of measures is showed in Fig. 8.

5.2 *Optical fiber sensing system*

Stimulated Brillouin Scattering (SBS) in optical fibers allows distributed measurements of strain and temperature over large distances and with high spatial resolution. SBS sensors rely on the dependence of the so-called Brillouin Frequency Shift (BFS) on the strain and temperature of the fiber.

In Brillouin Optical Time-Domain Analysis (BOTDA) sensors, the BFS along the fiber is retrieved by recording the interaction between a pulsed pump beam and a counter-propagating continuous wave probe as a function of time, while scanning the pump-probe spectral shift over a typical ~200 MHz frequency range. Any deviation of the local BFS from a reference measurement is a signature of strain or temperature change.

Figure 6. Weather sensors. The weather station started acquisition in December 2013.

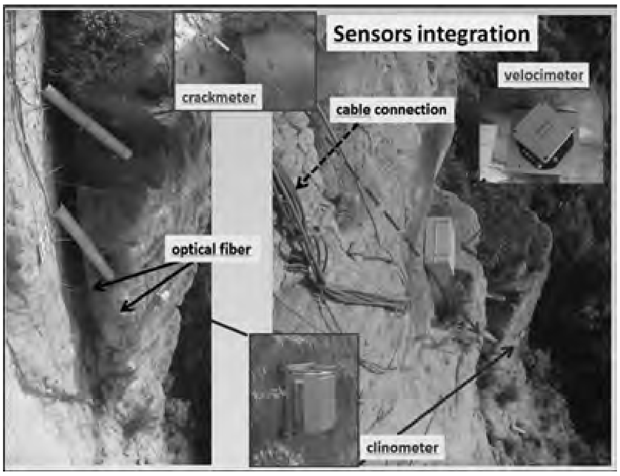

Figure 7. Example of sensor and cables employment on the cliff.

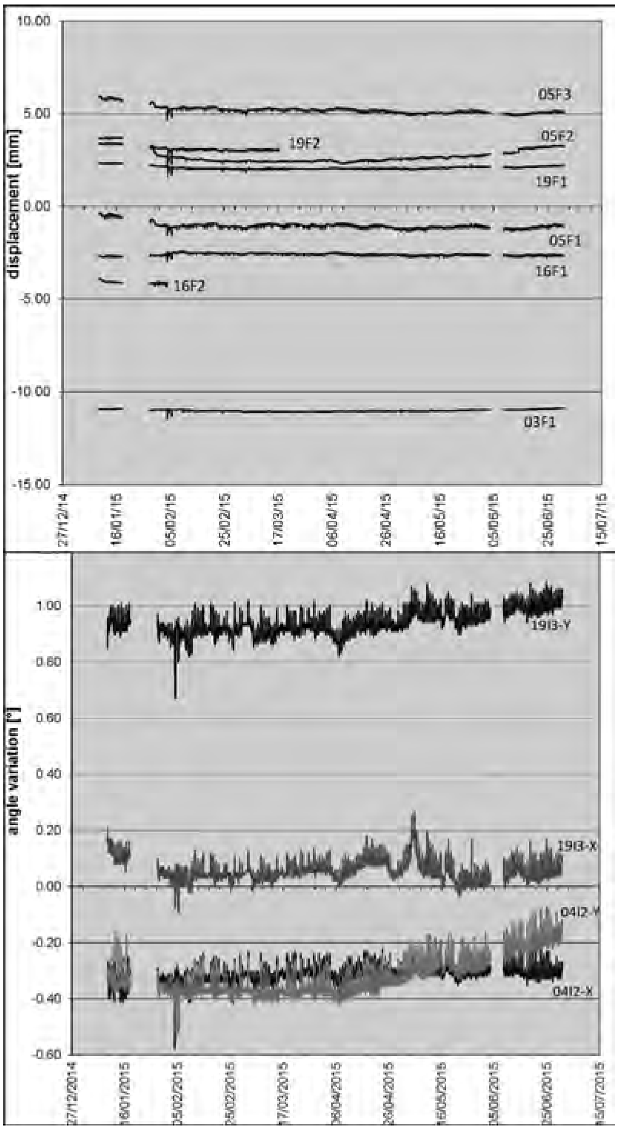

Figure 8. Diagrams of crackmeter dataset (upper) and clinometer and thermometer datasets (lower).

The BOTDA setup used for the strain measurements is shown in Fig. 9. The light from a distributed feedback laser diode (DFB-LD) operating at 1.55 μm wavelength is split into two arms to generate the pump and probe beams. Finally, a polarization scrambler (PS) is employed to average out the Brillouin gain fluctuations associated with variations of the state of polarization of the interacting beams.

The measurement unit allows to measure strain and temperature with a strain accuracy < 20 με, a temperature accuracy < 1°C and a spatial resolution of 50 cm.

The measurement fiber was composed by a 105-m long loose tube cable with dielectric protection, with 4 single-mode optical fibers mechanically insulated from the external environmental,

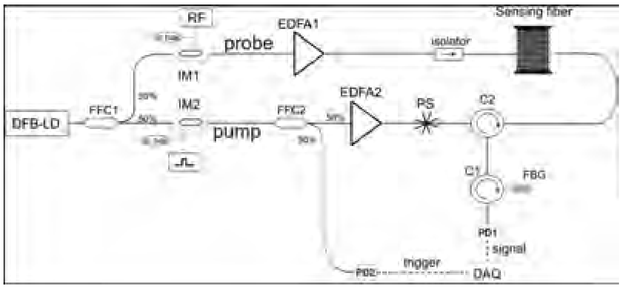

Figure 9. Scheme of the optoelectronic measurement setup. The lower part of the figure shows the generation of the pulsed pump, while the upper part shows the generation of the probe signal through double-sideband suppressed-carrier modulation and a fiber Bragg grating (FBG) that selects the sideband at the lower frequency (Stokes component).

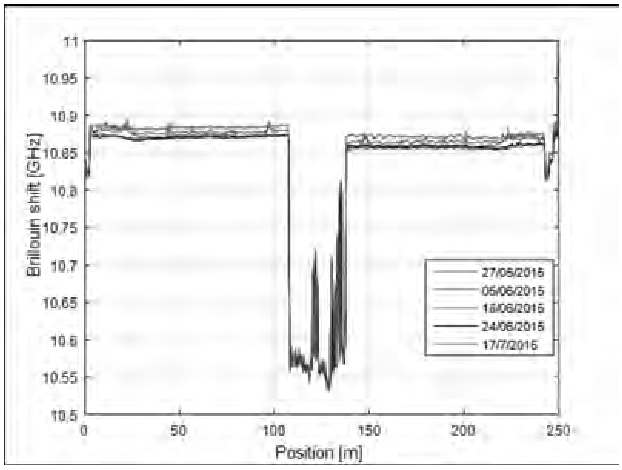

Figure 10. BFS measurements taken along the whole measurement fiber.

and a 30-m long strain sensing cable (V1 from Brugg) with only one fiber.

The outer diameter of the measurement fiber was 3.2 mm for the strain cable, and 6.4 mm for the loose tube cable. In order to realize the measurement loop needed in BOTDA measurements, two of the 4 fibers within the loose tube cable were spliced together, while the other two ends of the same fibers were spliced to the strain sensing cable. The V1 cable comprised between z_{in} and z_{out}, was fixed to a number of nails across the tuff blocks. In particular, two deployment zones were selected (point 3 and point 19) for optical fiber measurements.

Distributed strain measurements have been recorded since March 2015, thanks to an optical fiber strain sensing cable installed over two selected tuff blocks and connected to a BOTDA reading unit.

We report in Fig. 10 the BFS profile acquired along the measurement fiber during the monitoring campaign, at the spatial resolution of 50 cm (pump pulse duration: 5 ns).

We observe a step change in the BFS at positions z = 105 m and z = 135 m, due to the different BFS of the strain sensing cable compared to the loose tube. Also, we observe some vertical offset between the various curves, which is attributed to the effect of ambient temperature (about 1 MHz change of the BFS per °C).

In order to separate the effect of temperature from strain, we have applied a correction factor to each curve, thus obtaining the alignment of the various BFS profiles. It is to be noted that the fibers within the loose tube were not sensitive to strain, therefore their BFS has been taken as a reference for subtracting the effect of temperature.

The profiles obtained after temperature compensation are shown in Fig. 11. The BFS profiles, clearly show a number of peaks due to the strain acting on each fiber segment stretched between a nails pair, namely 3 peaks for monitoring point #3, and 4 peaks for monitoring peak #4. By comparing the various measurements taken during the survey, it is observed that the BFS changes are in the order of 20 MHz (corresponding to a strain of about 400 με). It can be recalled, as a reference, that a strain of 400 με over a length of 50 cm of stretched fiber, corresponds to a longitudinal displacement of about 200 μm.

5.3 *Dynamic system*

A tri-axial (Veloget-3D) sensor was installed on the cliff to detect and analyze the vibrations propagating in the medium (Fig. 5 and 6). This velocimeter, is characterized by a flat amplitude response in the range 1–256 Hz, and is integrated with a Dymas24-ALBEN acquisition system. The dynamic system installed on Coroglio has been set in order to operate under two modes of data recording. The standard mode implies the acquisition of maximum and minimum velocity on three components, every 60 seconds. This mode is useful to reduce the amount of data to record and transfer and, at same time, preserves the information concerning the vibration amplitude during long time periods (days or months). The second mode is based on the trigger approach with a buffer memory. If the amplitude, on one of the components, is higher than a fixed threshold level, the systems switches in a real-time recording mode (event-mode). This consists in a full signal registration at 500 Hz sampling rate, allowing for a detailed spectral analysis of the detected event. Moreover the buffer memory permits the recording of the signal even a few seconds prior to the occurrence of the threshold event.

The min/max values recorded during one month and one day are reported in Fig. 12.

It can be observed, as an example, that the higher magnitude events associated with the latest earthquake sequence occurred at Campi Flegrei on 7 October 2015 have been clearly recorded by the

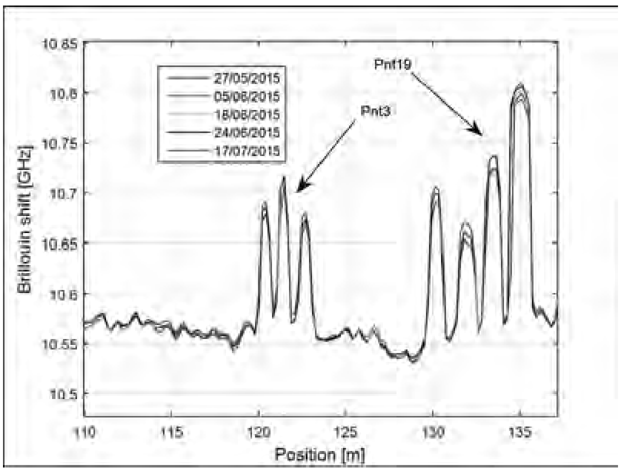

Figure 11. BFS measurements taken along the optical fiber cable installed on the tuff cliffs, after temperature compensation. The measurement region corresponding to the strain sensing cable are showed.

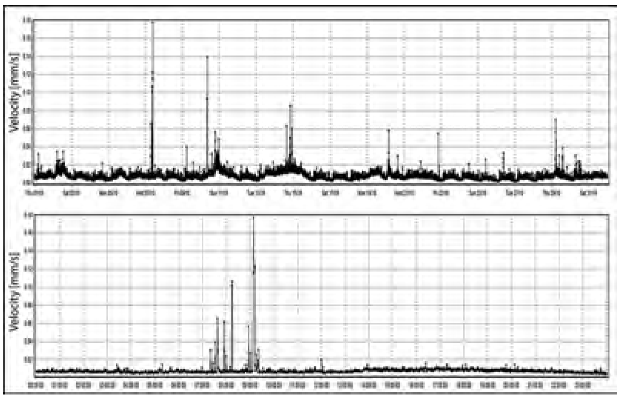

Figure 12. Minimum and maximum velocity values, recorded during the month of October 2015 (a) and during the day 07/10/2015 (b).

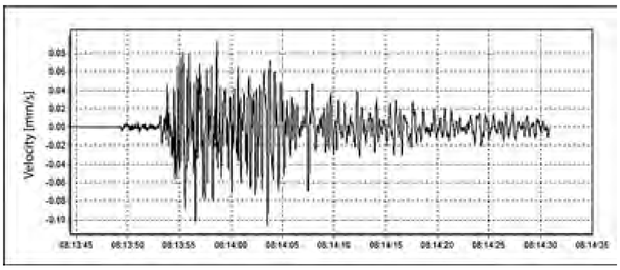

Figure 13. Seismic event recorded on 07/10/2015 at 08:15:50.

system (Fig.13). Frequency analysis of recorded signals has shown also a series of spikes around 170 Hz. However, additional data and analysis will be required to better understand and correlate the recorded spikes with local background noise and/or response of the medium in terms of precursors of cracking within the rock.

6 CONCLUSION

The Tuff Cliff Monitoring (TCM) project involved a section of the Coroglio tuff cliff (Napoli), characterized by instability processes causing tuff block failures in last years. The geomorphologic instability is due to several causes, such as the complex volcano-tectonic evolution, the strong anthropic modification of the territory and weathering and erosion processes occurring in the coastal area due to sea and weather actions.

Terrestrial Laser Scanner (TLS) data and structural field surveys allowed the geostructural analysis of the cliff and the detection of unstable tuff blocks on the cliff walls. Traditional geotechnical sensors and optical fiber devices have been installed across the fractures bordering these blocks in order to provide a multi-parametric and integrated monitoring.

The monitoring network planning was based on the choice of selected parameters to be investigated, such as the rotational or translational movement of tuff blocks along the cliff, variation in the opening of the fractures bordering the tuff blocks and the values of environmental, climatic or seismic parameters.

The TCM system is formed by 13 "static" sensors (9 crackmeters, 2 biaxial clinometers, 2 rock termometers), 1 "dynamic" sensor (triaxial velocimeter) and optical fiber cable and devices. The local monitoring is integrated with areal multi-temporal surveys by means of TLS and UAV.

The data acquisition and broadcasting system is of mixed type with remote-control for deformation, dynamic and weather data, and periodic lecture on site for optical fiber data; critical thresholds are set for seismic data with automatic warning.

Micro-deformation of rocks measured by static sensors reveal a general sinusoidal trend possibly linked to the background volume variation of the tuff mass, as a response to seasonal and daily temperature variations.

The main aims of the research are:

- Individuation of "normal" field of variation of geotechnical measures in the study area.
- Understanding of the contribution to the variation of geotechnical measures due to the temperature and other meteorological factors (rain, wind, humidity, atmospheric pressure, etc.).
- Definition of threshold levels for early warning related to block failures, which can be "dynamic" in order to take into account the different temperature regimen during the various "seasons" of a year.
- Definition by proper statistical methods of forecasting of an automatic procedure for an early warning system based on real time evaluation of differences between observed and predicted values.

Next steps of the research will be the integrated analysis of collected data and the definition of operational procedures for the real time monitoring and early warning of failures along the cliff. After their validation these procedures will be applied to other case studies in different geological and morphological contexts.

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