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An integrated approach for rock slope failure monitoring: the case study of Coroglio tuff cliff (Naples, Italy) – preliminary results

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***Abstract* – The paper reports the implementation of an integrated system aimed at the real-time monitoring of a series of physical parameters controlling the rock slope stability. The system has been installed on the Coroglio tuff cliff, located in the highly urbanized coastal area of Naples (Italy) at the border of the active volcanic caldera of Campi Flegrei. Preliminary results obtained during the first year of data acquisition and monitoring activity (December 2014 – January 2016) are also discussed on the basis of statistical models.**

I. INTRODUCTION

Monitoring of cliff stability is an essential task for the management of high-risk coastal urban areas. The use of monitoring systems is becoming a standard practice to assess and prevent geological and geotechnical hazards, as rock failures along slopes, and plan effective actions for risk mitigation.

Cliff failures have multiple predisposing factors, often depending on lithology, weathering and fracturing of rocks, exposure, as well as local meteorological and environmental conditions.

Several experimental monitoring systems are operative in mountain environments, such as in Swiss Alps [1] and Northern Apennines [2]. These systems have the purpose of detecting and measuring the small deformations of rocks that can be regarded as precursors of landslides.

The paper reports the implementation of an integrated system aimed at the monitoring of physical parameters controlling the rock slope stability in a complex case study. The system has been installed 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 complexity of the study resides in three main aspects: the lithology of the “soft rock” [3] exposed on the cliff (i.e. Neapolitan Yellow Tuff), the proximity of the coastline, and the volcanic unrest of the area. The preliminary results obtained during the first year of monitoring activity (December 2014 – January 2016) are discussed on the basis of statistical models.

II. COROGLIO CLIFF

The Coroglio cliff is 140 m high and 250 m wide. After a major rock fall that occurred in 1990, the northern sector of the upper part of the tuff cliff has been subject to reinforcement works, mostly consisting in steel bars anchored and bolted to the rock and a wire mesh and steel cable network applied to the tuff wall.

The upper part of the cliff displays slope angles varying from 35° to 45° and is represented by about 30 m of stiff to loose Holocene and recent pyroclastic deposits and very loose reworked volcaniclastic deposits at the top.

The median sector of the cliff displays a nearly vertical slope and is formed by two tuffaceous units, separated by an unconformity. The upper unit is formed by the Neapolitan Yellow Tuff (NYT) formation, represented by alternating coarse-grained matrix-supported breccia, thin-laminated lapilli beds and welded fine ash deposits. The NYT rock face displays a relatively homogeneous texture with several sub-planar surfaces likely controlled by structural discontinuities

According to Froldi [4], the Uniaxial Compressive Strength (UCS) of the NYT cropping out at Coroglio is characterized by an average value of σ_c 5.39 MPa, with a mean bulk density ρ of 1.46 Mg/m^3. Therefore the NYT can be regarded as weak to moderately weak rock, according to the classification of the British Standards Institution [5].

The lower unit is represented by the deposits of

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Trentaremi formation (TRF), that consists of slightly welded to welded, whitish to yellow, coarse-grained pumiceous fragments embedded in a sandy ash matrix and lapilli beds. The TRF face is characterized by diffused dm-scale vesicles and vacuoles due to differential erosion, markedly controlled by the bedding of the pyroclastic deposits. The base of the cliff is covered by slope talus breccia and gravelly beach deposits, mainly occurring along the shoreline.

A terrestrial laser scanner (TLS) has been used for obtaining detailed multitemporal digital terrain models (DTM) of the Coroglio cliff [6], as well as geostructural analysis of the tuff slope [7], supported by structural fieldwork. The NYT succession is characterized by a complex system of mostly steep and planar structural discontinuities and fractures [7] showing highly variable spacing, well-developed NE–SW and NW–SE directions, and subordinate N-S and E-W trends.

On the basis of a geomorphological analysis, including cliff inspections conducted by climber geologists, and interpretation of the DTM of the rock surface, two sectors with evidence of generalized instability have been recognized. Along these sectors, a series of prismatic tuff blocks > 1 m^3 bounded by open fractures have been identified. Structural measurements using traditional structural fieldwork methods allowed for the kinematic characterization of the unstable blocks and the design of the subsequent monitoring phase discussed in this study.

III. THE MONITORING SYSTEM

The monitoring system consists of standard geotechnical monitoring instruments (crackmeters and clinometers) coupled with a network formed by Brillouin Optical Time-Domain Analysis (BOTDA) sensors, a velocimetry sensor and a weather station. Measured parameters are: a) variations of distance across fractures within the rocks, b) variations of angle of rock blocks, c) rock temperature, d) rainfall, e) air temperature, f) humidity, g) wind, h) atmospheric pressure.

The location of monitoring stations installed on the Coroglio tuff cliff is reported in figure 1.

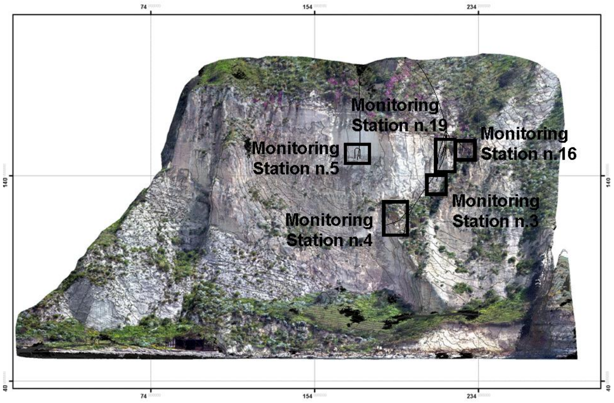

Fig. 1 – Location of monitoring stations installed on the Coroglio tuff cliff.

The Coroglio site is not served by electricity distribution network nor internet cable connection. Data transmission from the monitoring stations to the control room, located at CNR-IAMC research institute, has been set to a default 30 minute interval to preserve the supply batteries. The transmission time interval can be also adjusted and eventually set on continuous acquisition in case of relevant events (i.e. seismic swarm or critical rocks stability condition). The remote station set-up and the data transfer are based on GPRS/4G connection. Data are directly stored in a dedicated NAS system and converted to open access files.

A. Geotechnical sensors

Traditional geotechnical sensors and optical fiber distributed sensors have been installed across the fractures bounding unstable tuff blocks in order to provide an integrated monitoring. Monitoring stations are equipped as follows: station n. 3 (one crackmeter and a set of optical fiber); station n. 4 (one crackmeter and one biaxial inclinometer); station n. 5 (three crackmeters); station n. 16 (two crackmeters); station n. 19 (two crackmeter, one biaxial inclinometer, a velocimeter and a set of optical fiber).

Figure 2 illustrates the location of crackmeters at monitoring station n. 16, as well as a detail of the monitored fracture and the orientation of major sets of structural discontinuities that characterize the rock front.

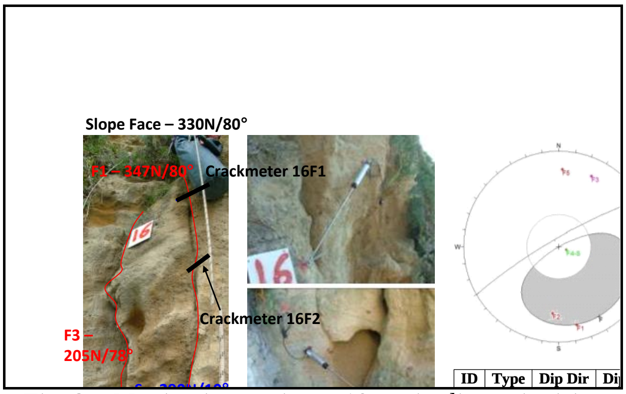

Fig. 2 – Monitoring station n.16: main discontinuities, location of crackmeters and kinematic analysis.

As shown in Fig. 2, the unstable block monitored at the station n.16 is compatible with a planar failure along the joint F2. In order to evaluate the influence of different triggering factors (rainfall, atmospheric pressure, seismic acceleration, temperature variations, etc.) on the stability of the block two continuous monitoring crackmeters were installed across the joint F2.

Figure 3 reports the temperature and displacement time series for crackmeter 16F1. Measured displacements and temperature essentially display the same general trends over the 1-year monitored period. Remarkable correlation also exists for the daily trends of displacement and temperature as indicated by the detailed plots for the time intervals reported in Fig 3b, 3c and 3d. This suggests a predominant elastic component of the deformation of rocks due to the daily temperature changes at the monitoring site. Such deformation displays a general sinusoidal pattern, ostensibly associated with a periodic variation of the bulk volume of rocks, as a response to daily as well as seasonal temperature variations.

Figure 3a highlights some divergence in the trends of temperature and displacement for the periods July-August 2015 and October-November 2015. The latter is probably linked to the local seismic activity recorded on the 7th of October and the 17th of November. The differences recorded during summer of 2015 (Fig 3c) are possibly due a different response of the sensors during a high temperature period.

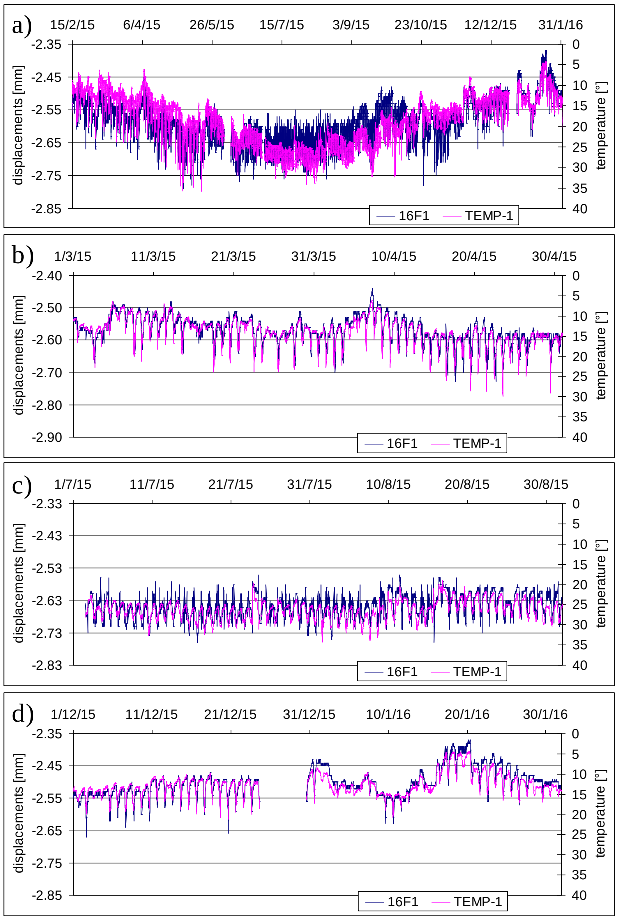

Fig. 3 – Temperature and displacement time series of crackmeter 16F1 for: a) the entire reference period; b) from 1/3/2015 to 1/5/2015; c) from 1/7/2015 to 1/9/2015; d) from 1/12/2015 to 1/2/2016.

B. Seismic sensors

In order to assess the dynamic behavior of the site, a tri-axial velocimeter has been also installed on the Coroglio tuff cliff. The scope is to record vibrations propagating in the medium and analyze a possible correlation with natural events and/or anthropic activities occurring in the area. This would provide, in principle, the possibility of detecting a typical frequency response for the cliff and consequently a way of defining a critical threshold for automated alerts.

The seismic sensor, characterized by a flat frequency response in the range 1-256 Hz and a sampling frequency of 500 Hz, has been set for acquisition with a threshold trigger method, meaning that recording only starts when a pre-fixed amplitude is exceeded by at least one of the three axis components. The minimum and maximum values, recorded every 60 seconds on each component, are also recorded and transmitted to the monitoring center. The combination of threshold approach and min/max recording values allows for the monitoring of both a long term (days to months) amplitude variations and the detailed frequency content of events.

The seismic sensor has been integrated with a Dymas24-ALBEN acquisition system, characterized by a double local storage memory system. The first one is a buffer memory, constantly refreshed with latest few second of signal, to be permanently stored when an event is detected. The buffer memory ensures the recording of the signal before the threshold exceedance. The second memory level, stores the min/max values and the event data before the transmission to the monitoring center. This storage memory also represent a full backup for the dynamic system.

Figure 4 illustrates an example of time signal (left) and the relative spectral amplitude (right) associated with a seismic event occurred on 7 October 2015.

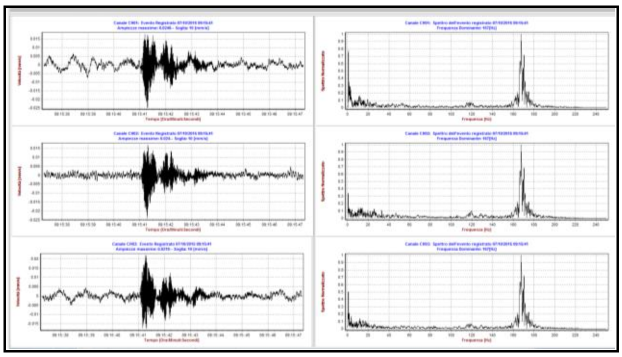

Fig. 4 – Time signal (left) and relative spectral amplitude (right) of an event occurred on 7 October 2015.

These data are relative to the higher magnitude events occurred on 7 October 2015, when an earthquake sequence affected the area. Similarly, most of the relevant earthquakes occurred in the Campi Flegrei have been recorded by the system.

Frequency analysis of recorded signals has shown also a series of spikes around 170 Hz. The understanding of the meaning of this frequency, and its possible correlation with local background noise and/or response of the medium in terms of precursors of cracking within the rock is currently under way.

C. Optical fiber sensors

Optical fiber BOTDA sensors exploit stimulated Brillouin scattering (SBS) in optical fibers to provide spatially distributed measurements of strain and temperature over long distances and with high spatial resolution. In particular, these sensors rely on the dependence of the Brillouin frequency shift (BFS) on the strain and temperature of the fiber. The BFS is retrieved by recording the backscattering of a pulse launched through the sensing fiber as a function of the time, while varying the frequency shift between the pulse and a counter-propagating probe field launched at the opposite end of the same fiber. Any deviation of the local BFS from a reference measurement corresponds to a signature of strain or temperature change [8, 9].
The BOTDA setup used for the strain measurements is shown in Fig. 5.

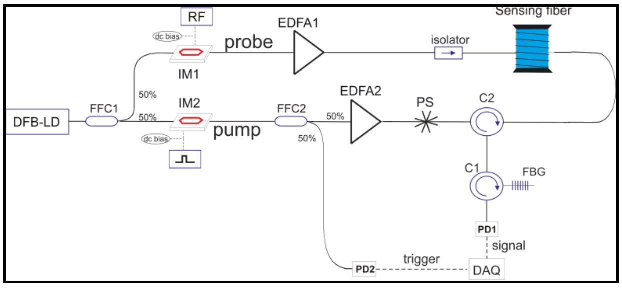

Fig. 5 - Scheme of the optoelectronic measurement setup.

The light from a distributed feedback laser diode (DFB-LD) at 1.55 µm wavelength is split into two arms to generate the pump and probe beams. The measurement unit allows to measure strain and temperature with a strain accuracy < 20 µε, a temperature accuracy < 1°C and a minimum spatial resolution of 50 cm. The measurement fiber is composed by a 105-m long loose tube cable including 4 single-mode optical fibers mechanically insulated from the external environment, and a 30-m long strain sensing cable (V1 from Brugg) with only one fiber. The outer diameter of the measurement fiber is 3.2 mm for the strain sensing 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 splicing the other two ends of the same fibers to the strain sensing cable (see fig. 6). The V1 cable 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. We report in Fig. 7 a summary of the BFS profiles measurements taken during the measuring campaign.

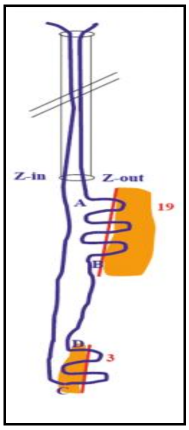

Fig. 6 - Sensing fiber cable path with indication of the monitored tuff blocks (block #19 and block #3).

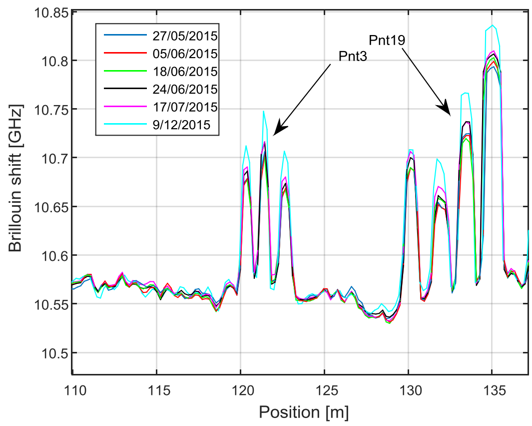

Fig. 7 – BFS profile measured along the optical fiber, after temperature compensation.

Note that the various profiles have been vertically corrected in order to consider the temperature dependence of the BFS. The strain peaks associated with each fiber segment stretched between a nail pair is clearly visible. By comparing the various measurements, it is seen that maximum BFS changes are in the order of 30 MHz, which correspond to about 600 µε. We interpret these changes as due to ambient temperature-related dilation/contraction of the rock masses at which the fiber segments are bonded.

IV. STATISTICAL APPROACH FOR EARLY WARNING

In order to investigate the correlation between meteorological parameters (mainly air temperature) and deformation of the rock mass, we have analyzed [10] two datasets, referred respectively to winter period and summer period, characterized by different climate regimen and no lack of data. Particularly, we have considered the time series corresponding to the period from 4/12/2014 to 19/12/2014 (autumn-winter) and the time series representing the period from 9/6/2015 to 29/6/2015 (spring-summer).

The main aims of the research are the definition of the "normal" background range of variation of geotechnical parameters in the study area, and the understanding of the contribution of temperature and other meteorological variables (rain, wind, humidity, atmospheric pressure, etc.) to the variability of geotechnical measurements. The final aim is the research of an appropriate forecast model.

In Fig. 8, the summer and winter time series acquired by geotechnical sensor n. 16F2 are compared with temperature.

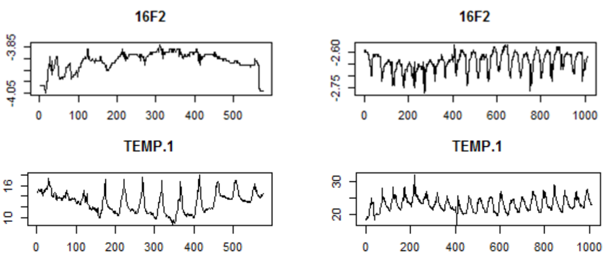

Fig. 8 – Comparison of measurements of crackmeter 16F2 with temperature during autumn-winter period (left) and spring-summer period (right).

For each period, we estimated the main statistical features (trend and seasonality) of measured time series (Fig. 9), which denote several differences between the two periods.

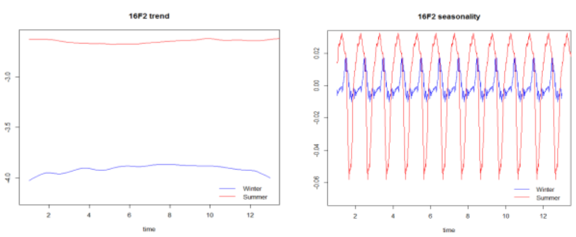

Fig. 9 – Statistical features (trend and seasonality) of time series of crackmeter 16F2 during winter (blue line) and summer (red line) periods.

A cluster analysis approach on time series of the two selected periods has been performed to understand the varying correlations between acquired data series and the meteorological factors from winter to summer period. The adopted analytic approach is known as Future Based Clustering Approach [11]. This method applies cluster analysis to point values based on global parameters depending on the whole time series. The measures obtained from each individual series can be fed into independent clustering algorithms, including an unsupervised neural network algorithm, self-organizing map, or hierarchal clustering algorithm. Since the cluster analysis is applied to extracted global measures, it reduces the dimensionality of the time series and is relatively unaffected by missing data and/or noise. Figure 10a and 10b show the results of the cluster analysis referred respectively to the summer period and winter period.

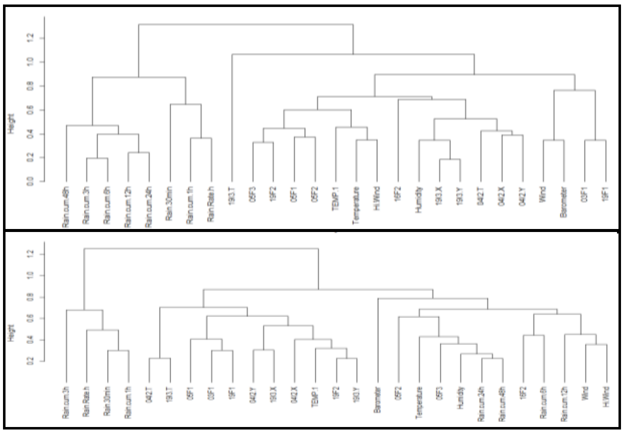

Fig. 10 – Results of cluster analysis for a) summer period and b) winter period.

Preliminary interpretation of data indicate that for a number of geotechnical sensors there is not any apparent correlation between rock deformation and meteorological parameters, whereas in other cases (e.g. for sensors 19F1, 16F2, 05F1 05F2, and 1913X) remarkable correlation can be observed. Therefore, we opted for two different forecast models [12], one for winter and another for summer, for the detected sensors.

We adopted a forecast procedure based on the use of both Exponential Smoothing State Space Model (ETS) and AUTOARIMA (with seasonality). The final output of the procedure (obtained with the forecast package for R) is obtained by a combination with equal weight of the two approaches.

The combination of different forecasts implies that the underlying process cannot be readily identified, but a wider spectrum of relevant information can be made available for prediction. Combining forecasts is especially convenient when selecting the best approach, out of a range of possible analytical methods, and also useful to minimize errors [13].

A thorough evaluation of the different approaches is obtained by considering the relevant indexes of adequacy for each model. In particular we have considered the MAPE (Mean Average Percentage Error) index. Preliminary results appear to be good [10], as in the 90% of cases we obtain a MAPE under 5. In particular Winter MAPE index ranges from 0.004 to 0.11 while in Summer MAPE index ranges from 0.164 to 0.573.

V. CONCLUSIONS

Micro-deformations of rocks measured by geotechnical sensors reveal a general sinusoidal pattern, likely associated with a periodic bulk volume variation of rocks, as a response to seasonal and daily temperature variations.

Next steps of the research will include: 1) integrated analysis of all datasets and the definition of operational procedures for the real time monitoring and early warning of failures along the cliff; 2) definition of "dynamic" threshold levels for early warning related to block failures, according to the changing temperature trends during the year; 3) definition of an automated forecasting procedure addressed to an early warning system based on real time detection of differences between observed and predicted values.

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