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Investigating Rock Mass Failure Precursors Using a Multi-Sensor Monitoring System: Preliminary Results From a Test-Site (Acuto, Italy)

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Abstract

In the last few years, several approaches and methods have been proposed to improve early warning systems for managing risks due to rapid slope failures where important infrastructures are the main exposed elements. To this aim, a multi-sensor monitoring system has been installed in an abandoned quarry at Acuto (central Italy) to realise a natural-scale test site for detecting rock-falls from a cliff slope. The installed multi-sensor monitoring system consists of: i) two weather stations; ii) optical cam (Smart Camera) connected to an Artificial Intelligence (AI) system; iii) stress- strain geotechnical system; iv) seismic monitoring device and nano-seismic array for detecting microseismic events on the cliff slope. The main objective of the experiment at this test site is to investigate precursors of rock mass failures by coupling remote and local sensors. The integrated monitoring system is devoted to record strain rates of rock mass joints, capturing their variations as an effect of forcing actions, which are the temperature, the rainfalls and the wind velocity and direction. The preliminary tests demonstrate that the data analysis methods allowed the identification of external destabilizing actions responsible for strain effects on rock joints. More in particular, it was observed that the temperature variations play a significant role for detectable strains of rock mass joints. The preliminary results obtained so far encourage further experiments.

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1. Introduction

In the last few years, more attention has been focused on the monitoring of fast to very fast failures, which include landslides from rocky slopes, e.g. rock falls, topples and wedge sliding. The relevance of such events is mainly related to the short time available for taking action in the case of exposed infrastructures (i.e. highways and railways) as no significant displacements are generally detected before failure. To create a comprehensive detection strategy, a coupled monitoring system can be adopted: i) monitoring precursors by using micro- or nano-seismometric devices as well as acoustic emissions [1–3] and ii) monitoring the rock fall source areas as well as the threatened infrastructures, by using optical devices able to detect fast to very fast changes of the observed scenario or the presence of anomalous objects that can clutter the infrastructure [4–9].

In the framework of the aforementioned strategy, the recognition of precursors in case of abrupt failures is an important target to mitigate the related risk from geological hazard. Changes in stress conditions of rock masses due to impulsive and viscous deformations can cause rapid and violent failures [10]. Sequences of microseismic events can proceed from a transitional to a transgressive phase so indicating imminent rock mass failures [11]. Failure precursors have already been detected by use of acoustic as well as seismometric devices [2, 12, 13]. In this regard, the implementation of microseismic arrays into a multi-parametric monitoring system can be considered a useful tool for mitigating the natural risk in early warning perspective. The analysis of sequences of precursors and post-failure events can be indeed useful for managing early preventive interventions, since monitoring phases of failure propagation provides information on changes involving the rock mass, but also on possible occurrence of more critical conditions.

A multi-disciplinary collaboration at the Research Centre for Geological Risk (CERI) of the University of Rome Sapienza planned and designed an in situ laboratory for a multi-sensor installation to carry out specific tests under natural and forced conditions and evaluate the suitability of multi-parametric approaches to manage the early-warning for infrastructure targets. Thanks to the availability of an abandoned quarry, provided by the Municipality of Acuto, the designed multi-sensor device was installed starting from autumn 2015.

The final goal of this test-site is to determine and improve control indexes for identifying several alert levels suitable to manage infrastructures in order to mitigate geological risk and reduce the response time for interventions.

2. Geological setting of in-situ laboratory site

The Acuto (central Italy) quarry (Fig. 1) was totally excavated on a carbonate hill, which is part of the Mt. Ernici ridge. The quarry area is located NE of Acuto village, where Mesozoic calcilutites with rudists crop out in the quarry walls. Bedding, which has a shallow dip out of the quarry face, is offset by NW-SE striking steeply dipping normal faults that have 10 m offsets [14]. The quarry wall where the monitoring system was installed is SE exposed and corresponds to the NW boundary of the quarry that is characterized by heights ranging from 15 m up to 50 m and by lengths of 500 m.

Before installing the multi-parametric monitoring system, geomechanical scanlines were performed on the selected quarry wall, following the ISRM standards [15] in order to characterize the rock mass and to choose the joints to be monitored during the experiment. Four joint sets were distinguished and their average attitudes are: S0 (130/13; dip direction, dip) corresponding to the limestone strata, S1 (270/74), S2 (355/62) and S3 (190/64). The average uniaxial compression strength of the rock, determined by Point Load tests, results to be 84 MPa. According to Deere & Miller [16], this result corresponds to a stiffness value of about $6 \cdot 10^4$ MPa. The rock mass characteristics have been described using RMRb classification [17], which assigned to Mesozoic limestone a score of 68.

A rock block of size amounting to 64 m^3 was selected as a main focus of the multi-parametric monitoring system; it is isolated by several joints and densely cracked. Such a jointing condition allowed the set-up of a sensor network, monitoring several discontinuities. Moreover, the block dimensions are suitable for optical monitoring by smart cameras and its location is favourable for installing nanoseismic networks to record failure precursors.

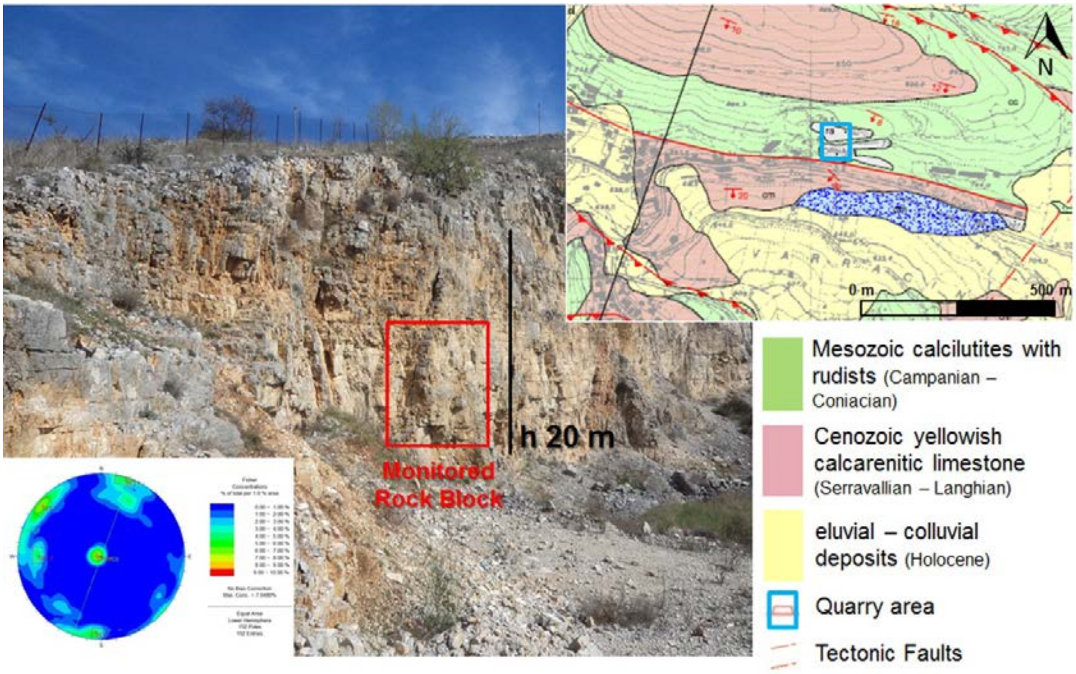

Fig. 1. Detailed view of the Acuto quarry wall. The monitored block (64 m^3) is delimited by the red frame; geological scketch of the Acuto hill and stereonet of joints are also shown.

A main fracture separates the backside of the block from the rock mass so that the block is protruding respect to the adjacent quarry wall where a railway track was posed as a target for falling blocks (see Fig. 2). The geometry of the block as well as the orientation of the joint sets in the adjacent rock mass predispose it to rock falls and topples that can involve the railway target of the experiment.

3. Multi-sensor monitoring system

The multi-sensor monitoring system was installed on the rock block in autumn 2015 and consist of:

- 2 weather stations (a conventional one and an innovative open source cloud system TSA-BOX) equipped with air-thermometer, hygrometer, pluviometer and anemometer for wind speed and direction. The stations were installed at foot and at top of the slope;
- 1 thermometer to measure the rock mass temperature, installed at the center of the monitored rock block;
- 6 strain-gauges installed on micro-fractures of the rock mass, corresponding to main joint sets;
- 2 extensimeters with 25 mm measure range installed on open fractures;
- 1 extensimeter with 10 mm measure range installed on transversal fracture;
- 1 joint-gauges with 100 mm measure range, installed on a large fracture at the back-side of the monitored rock block;
- 1 optical cam (Smart Camera – Wireless Sensor Network WSN) connected to a customized Artificial Intelligence (AI) system: the WSN was intended to detect morphological anomalies, such as rock slopes prone to falls, and the presence of unexpected objects along the monitored railway target. A WSN, which can transmit real-time data, can provide early warning [18];

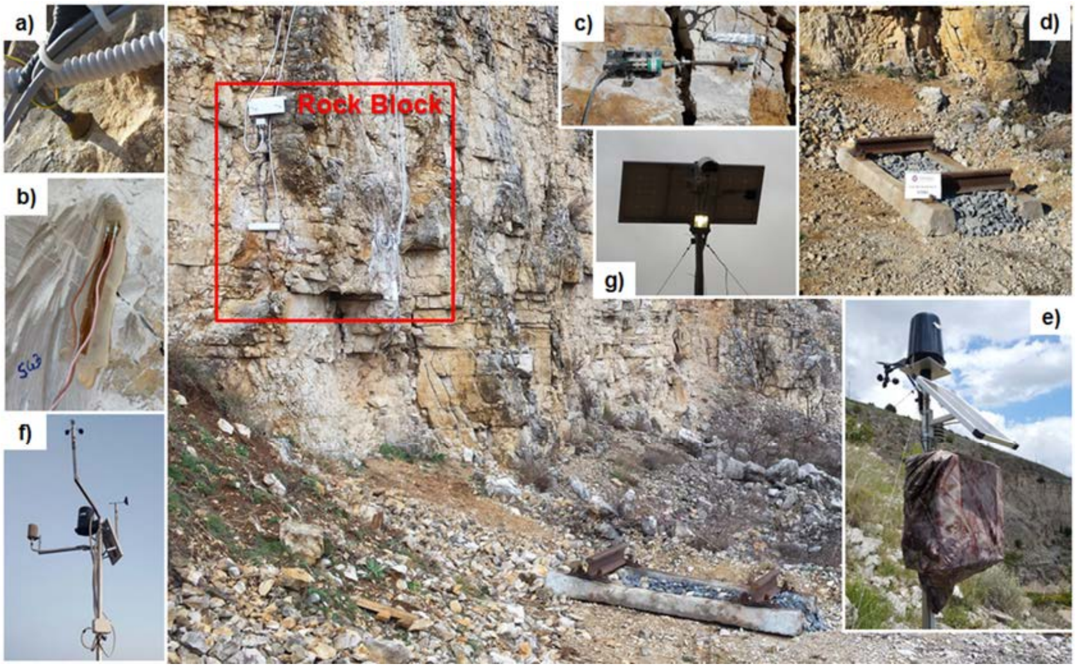

Fig. 2. Monitored rock block (red frame) with the railway track (d) located at its base and used as original target for the optical sensor. Sensors installed on rock block: a) thermometer to measure the rock mass temperature; b) strain-gage; c) extensimeter. In-situ devices are connected to data-logger CR1000 Campbell Scientific with incorporate meteo-station (e). Innovative meteo-station (f) and optical cam are also shown.

- Seismic monitoring device and nanoseismic array for detecting and locating possible microseismic trigger events of rock failures on the cliff slope were also temporary installed for multi-hour recording.

More in particular, the different geotechnical monitoring devices were installed on micro-fractures and open-joints predisposed for rock-fall and wedge sliding phenomena for detecting changes in the stress-strain conditions of the monitored block.

Strain-gage sensors have a micrometric sensitivity, while the other strain sensors have a sensitivity of 0.01 mm and all of them are set to automatically download each minute. The recorded data are stored in a local data-logger CR1000 Campbell Scientific, equipped with 24 acquisition channels. The system is completed by an automatic data transmission device, equipped with a GPRS wireless connection system; the data are sent to a local server that allows complete data storage every 4 hours and enables remote control of the dataset.

4. Preliminary results from the multi-sensor monitoring system

4.1 Experiments in natural conditions

The experiments planned at the Acuto test-site will be performed over at least 1 year and will be carried out in two different phases, namely A and B. In the first phase, weather and stress-strain monitoring will be carried out by continuous recording to detect seasonal changes due to temperature, wind and precipitation that can influence the rock mass deformations. These specific weather conditions can induce stresses in the rock mass joints also detected by the AI optical system. A possible cluttering of the railway target can be detected by the AI-tech optical system (Fig. 4) while precursors of rock failure can be detected by in-situ devices in terms of both stress-strain effects and micro-seismicity.

During the phase A, which started in January 2016, the attention was focused on the strain device installed on the monitored rock block and on the crack opening trend. More in particular, the rock block was instrumented with 4 strain-gauges and 2 extensimeters on the front side with the aim of capturing precursory signals of rock falls; moreover 2 strain-gauges, 1 extensimeter and 1 joint-gauge were installed on the backside with the aim of recording precursory signals of tilting or toppling. To detect variations of strain rates as an effect of forcing actions, the continuous recorded data are managed following two different approaches: an Observation-Based Approach (OBA) and a Statistic-Based Approach (SBA). The goal of these approaches is to forecast the slope evolution by identifying precursors of rock mass failure, thus providing alert levels suitable for managing infrastructures in order to mitigate landslide risk and reduce the response time for intervention. The first approach is focused on searching objective correlations among forcing triggers and induced effects; the second one adopts statistically based cross correlations among different continuously recorded parameters to point out anomalies in their trends as well as scatter of cumulative values.

The strain rates were automatically computed through a customised script encoded by SAC (Seismic Analysis Code) and FORTRAN software on UNIX platform. The script performs some pre-processing operations on individual time histories from the multi-parametric monitoring system. It mainly smoothes the data from the weather station and removes possible anomalous spikes from the strain and rock temperature data. Finally, it calculates the linear regression, the R^2 factors and the rate on temperature, cumulative precipitation, wind velocity and strain time series.

The obtained data were processed following the OBA and the SBA. According to the OBA the time histories of the measured values were visually compared to point out objective correlations (i.e. trigger vs. effect conditions). The rate of the strain gauges is expressed in micro-strain and the temperature influence is compensated directly in the datalogger firmware by using a compensation value for each sensor. Following the SBA, cross-correlation functions were defined between rate of air and rock temperature as well as between rate of rock temperature and strains. Figure 3 shows an example of a very high cross-correlation (i.e. measured by the Cross-Correlation Function - CCF) between air temperature rate and rock temperature rate and between micro-strain rate and rock temperature rate.

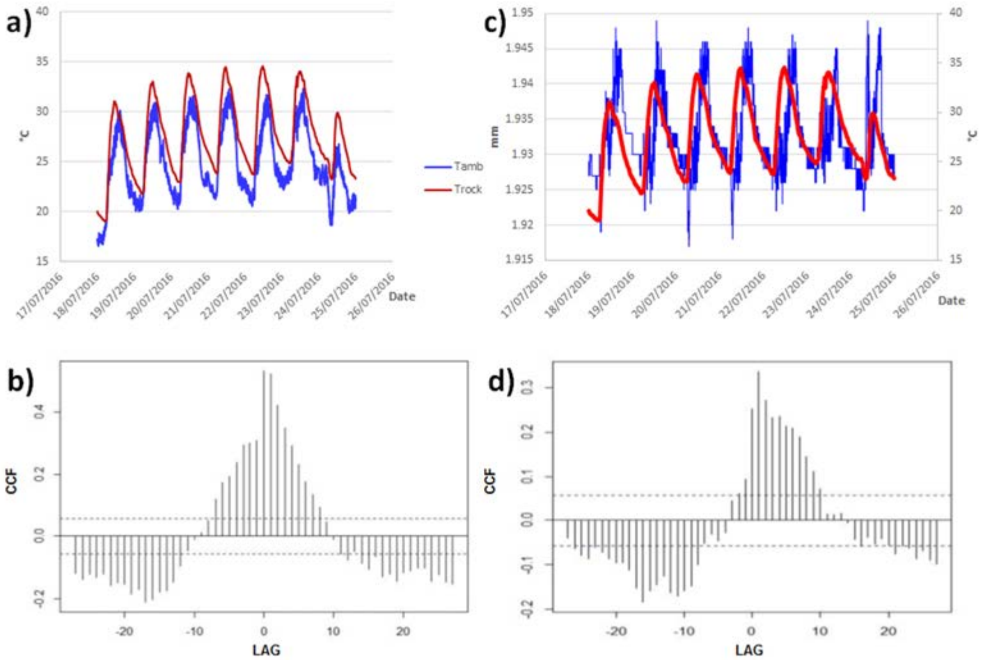

Fig. 3. Example of OBA (a and c) using the time series and the SBA using the rate cross-correlation (b and d) in case of air temperature vs rock temperature and in case of rock temperature vs. joint strain. For graphs that show the SBA results (b and d) the CCF value is plotted on y axis; the time LAG is plotted in x axis: a LAG units is equal to the sampling step (10 minutes) in which the rate of the series was calculated.

The same results can be obtained also by the OBA, comparing the time sequence of air and rock temperature and of micro-strain and rock temperature. As it results by the cross-correlation and by the objective correlations rock temperature represent a possible trigger since its variation systematically anticipates joint deformations. More in particular the delay time with which a forcing action influence the rock behavior and involves a deformation response, measured by the cross-correlation, is equal to or less than 10 minutes.

Sensitivity analyses were also performed over several days when particularly intense meteorological conditions (i.e. high rock temperature, intense rainfall and strong wind) were detected, representing potential destabilizing actions. Following the SBA, cross-correlations were carried out among rate of intensity of each considered forcing action and rate of joint strain. The obtained results show that rainfall and wind are poorly cross correlated with the rock mass strain. On the contrary, the rock temperature reveals a good cross correlation with the rock mass strain, i.e. demonstrating a significant influence on the rock mass deformation. In this case, no significant lag between action occurrence and recorded effect was observed; this means that the high rock temperature can be regarded as a destabilizing action which can cause a response of the jointed rock-mass in a short- to very-short (into 10 minutes) time window.

In this preliminary experiment both the SBA and OBA demonstrated the possibility to detect and provide an early warning; the lag time between the event detection and the alert signal is well identified by the CCF obtained by application of SBA. Both of the applied approaches identified which forcing actions influence monitored strain effects. Nevertheless, further data and processing will allow the determination of a statistical representativeness of the two approaches for early warning strategies, pointing out their suitability and the corresponding reliability level for different scenarios of rock fall trigger.

4.2 Experiments in forced conditions

In July 2016 the second phase (B) of the experiment was partially carried out. The monitored wall was artificially forced by static, pseudostatic and dynamic actions to induce stress-strain effects under controlled conditions. During the forced experiments, possible cluttering of the railway target as well as precursor of rock detachments were detected by the installed multisensory monitoring system.

For the forced experiments, the monitoring system was implemented with remote and on-rock accelerometers in order to better investigate precursor of rock mass failure. More in particular, 6 on-rock sensors mono-axial accelerometers KINEMETRICS FBA11 were installed: 2 on block front side, 2 on block back side, 2 outside the block; they were cable connected to a KINEMETRICS K2 datalogger, provided with a tri-axial accelerometer, placed at the foot of the slope and acquiring in continuous mode with a sampling frequency of 250 Hz. A Seismic Navigation System (SNS) array, following a recently proposed nanoseismic monitoring approach [19], was installed in the central part of the quarry, close to the monitored block. This technique allows the identification and location of precursory signals as well as the impact point of rock falls. The aim of nanoseismic monitoring is to locate weak seismic events with negative magnitude, under low SNR (Signal to Noise Ratio) conditions. The installed SNS array consisted of one central three-component station and three outer vertical stations, positioned with an aperture of 25 m. Each station was equipped with one LE-3Dlite MkII seismometer (Lennartz Electronic GmbH) and one REFTEK 130-01 data-logger that acquired with a sampling frequency of 500 Hz. A further remote sensor implemented into the multi-parametric monitoring system was a terrestrial interferometer installed in front of the selected rock block.

Both the SNS array and the terrestrial interferometer recorded in continuous mode from 18th July to 21th July 2016, while dynamic actions were applied to the slope for detect instability events. For this purpose, a vibrodyne was located on a concrete base at the foot of the instrumented rock block and was operated to induce frequencies in a range between 5 Hz and 30 Hz with incremental step of 5 Hz interspersed by a pause that had the aim to allow the slope system to reach a new balance after the induced stress (Fig. 4). In the same way, a pseudostatic action were applied to the slope to induce rock falls. Some small rock blocks, to the side of monitored block, were made mechanically to fail. In this experiment attention was paid to the SNS array, which can be able to record the micro-fracturing and the precursory signals of the rock falls and locate them in 3D space. During this experimental phase, 3D multi-time scans were also collected by terrestrial laser scanner technique as well as SFM technology of the rock block for detecting morphological changes due to the induced stresses. To test the change detection analysis

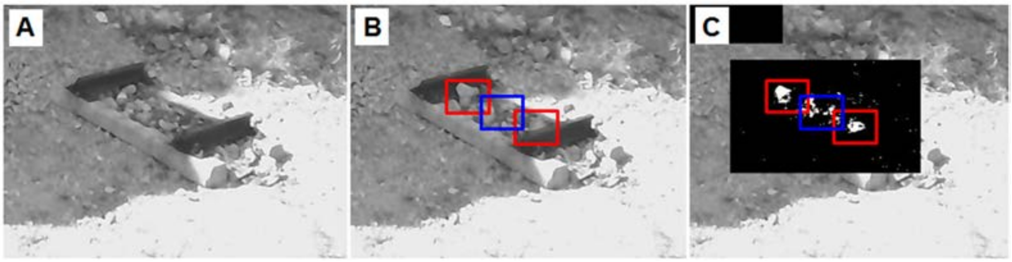

Fig. 4. Example of change detection analysis performed by the AI-tech optical cam: A) background image; B) size-defined rock block on the target (red frame) and ballast moved due to block rock impact (blue frame); C) pixel changed is detected and can trigger an alarm signal.

performed by AI-tech optical cam on the monitored railway target, a check of presence/absence of objects on the target was carried out thanks to size-defined rock block for testing the alarm threshold set (Fig. 4).

A spectral analysis will be performed on the recorded accelerometric data (Fig. 5) to investigate changes in frequency content and noise intensity, which will be correlated with the strain rate records from the geotechnical system.

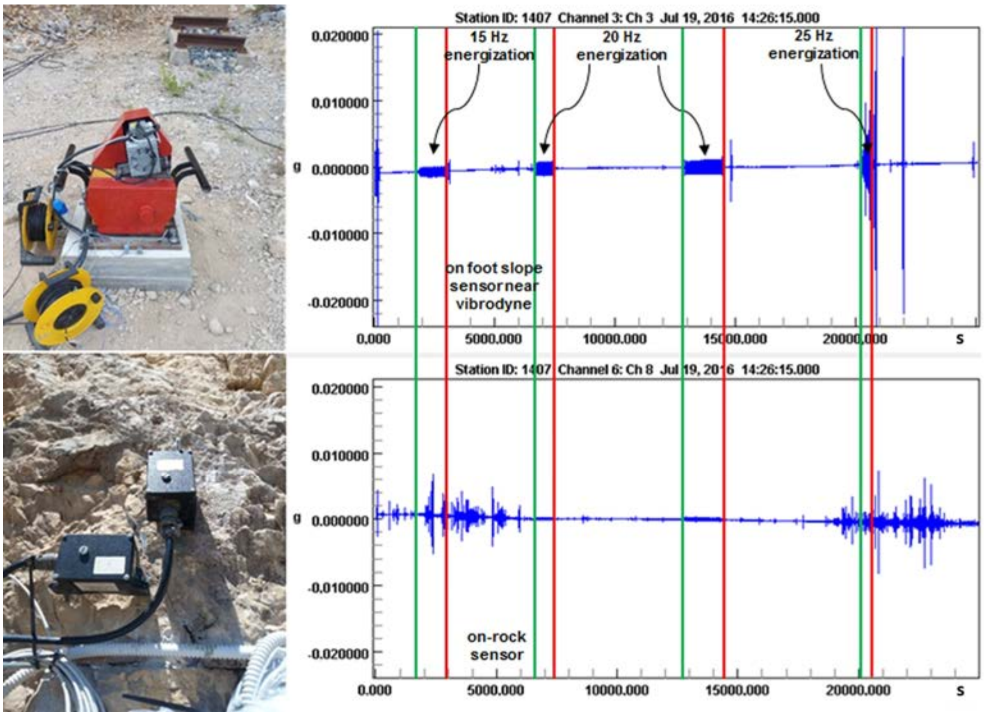

Fig. 5. Accelerometric record of the dynamic action induced on the rock block by a vibrodyne, recorded at the foot slope (up) and by one on-rock sensor (down). Green line mark the input start; red line mark the input stop. The on-rock acelerometer shows how the block continues to vibrate for a few minutes after the dynamic input termination. On the left, thevibrodyne (up) and two on-rock accelerometers (down) are shown.

Conclusion

Experiments for testing multisensor monitoring devoted to rock falls precursors and effects are still in progress at the Acuto (central Italy) test site. The final aim is to determine strategies for managing multiparametric acquisition for early warning. Two different approaches of analysis were applied so far: the Observation-Based

Approach (OBA) and a Statistic-Based Approach (SBA). The preliminary tests demonstrate that both the OBA and the SBA allowed the identification of external destabilizing actions responsible for strain effects on rock joints. More in particular, it was observed that temperature variations play a significant role for detectable strains of rock mass joints. On the contrary, precipitation and the wind velocity do not seem to trigger strain responses on the rock mass joints. Moreover, preliminary experiments were carried out in forced conditions, applying dynamic actions, by monitoring seismic wave propagation within the rock wall, vibrational behavior of jointed rock blocks and strain rate of the rock mass. An AI-tech optical cam system was also tested for checking the presence of rock blocks on a railway target located at the bottom of the monitored rock wall: thanks to on-board change detection analysis an alert signal can be sent in case of railway target encumbrance.

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