Comparison of microseismic-event and ambient-noise strategies for rock-mass monitoring

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~~2D ERT (WENNER-SCHLUMBERGER) ACQUIRED IN THE PRESENCE OF GRAVES WITH FLOATING ELECTRODES IN ARRAY~~*

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*nella versione a stampa finale dei Riassunti Estesi delle Comunicazioni GNGTS 2016, il lavoro è stato pubblicato con un titolo ERRATO rispetto al titolo originale del lavoro sottomesso, a causa di problemi di copy editing. E' preservato tuttavia per intero il contenuto del lavoro.

Introduction. Unstable rock mass in highly populated areas draw attention to the need for appropriate monitoring techniques due to their sudden energetic release and large destructive power. In this work we present the results of a seismic-based characterization and monitoring campaigns, carried out on a prone-to-fall granitic cliff in northwestern Italy (Madonna del Sasso, VB). The frontal portion of this cliff is free on three sides (Fig. 1a) with high vertical walls (150 m) directly exposed on the roads, houses and small factories located on the western shore of Orta Lake. The top of this area is affected by four main fracture families, which almost isolate two unstable sectors (A and B, with an estimated volume of 12,000 and 7,500 m^3 respectively) and show a complex intersecting 3-D pattern (Fig. 1b). The steep morphology and the limited accessibility of the cliff led to a site-specific approach to the understanding of its behavior. Considering the growing people's awareness of the natural risk related to the site, a monitoring campaign with unconventional methodologies, devised on the basis of the preliminary seismic characterization, appeared the best choice to control the evolution of the phenomenon. Four triaxial geophones were installed on sector A, with ST1 and ST2 located at the foot of the block, ST3 placed at the top of the rock column and ST4 settled outside the fractured area, in order to be used as a reference station (see again Fig. 1a for the location of the stations). Particularly, in this work we focus on the comparison between the outcomes of microseismicity (event detection, location and time rate) and ambient seismic noise (spectral analysis and cross-correlation) techniques.

Seismic characterization campaign. Although the site setting made the characterization study very challenging, geophysical multiscale tests provided new and valuable information for assessing the rock instability (Colombero *et al.*, 2015). Particularly, the seismic surveys

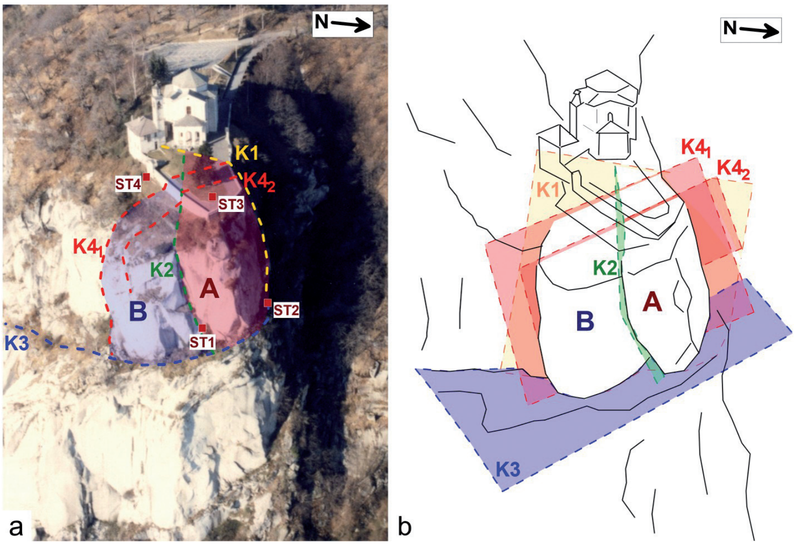

Fig. 1 – Aerial (a) and schematic (b) view of the cliff of Madonna del Sasso (NW Italian Alps), with traces and 3-D reconstruction of the main fracture planes affecting the frontal portion. The unstable sector A (in red) and B (in blue) have an estimated volume of 12,000 m^3 and 7,500 m^3 respectively. The station of the microseismic monitoring network are reported with red squares (ST1-ST4, in a).

allowed investigation of the fracturing state of the granitic cliff at depth, which helped to better understand the geometry of the unstable sectors and to define a velocity model for the site, fundamental for the location of the detected microseismic events.

Considering the complex morphological and geological context, cross-hole tomography contributed to spatially image the seismic-velocity field of the site, enabling to locate the fracture zones and the related velocity contrast. Conversely, downhole tests helped to define more punctual velocity values and to better calibrate the seismic field. Laboratory measurements of ultrasonic pulse velocities on a variety of samples collected at the site revealed to be a fast and simple method to lithologically interpret the field data, with a good agreement between the results at different scales. Density and porosity laboratory measurements on granite samples allowed also to associate the different seismic velocity ranges to different macroscopic peculiarities (e.g. weathering conditions and presence of anisotropy) of the granites.

Moreover, processing of surface shot seismograms in time and frequency domain, together with surface-wave analysis, revealed the best way to constrain fracture opening in depth (e.g. in Bièvre *et al.*, 2012; Bergamo and Socco, 2014).

All the results confirmed the presence and persistence of deep and pervasive fractures within the rock mass which isolate the prone-to-fall frontal portions of the cliff.

Passive seismic monitoring. For monitoring purposes, passive seismic techniques were applied on the prone-to-fall compartment using two different approaches. The first approach consisted in detecting an increase in the number of seismic events and/or a rise in seismic energy over a given period of time, which could indicate a destabilization of the unstable mass (e.g. in Senfaute *et al.*, 2009; Lévy *et al.*, 2010). No evidence of acceleration to failure was identified during the monitored period (October 2013 - present). Proper location of microseismic events, using a calibrated 3-D velocity model, revealed to be quite challenging given the complexity of the site and of the resulting wave field. A concentration of low-energy releases close to the major fracture planes affecting the rock mass, particularly along K2 and K4, could be however depicted (Fig. 2).

The second approach involved the processing of ambient seismic noise, in order to focus on the dynamic behavior of the whole unstable rock mass (see Larose *et al.*, 2015 for an overview of the methods and potential applications). The spectral content of seismic noise systematically highlighted clear energy peaks on the unstable sector, which were interpreted as the resonant frequencies of the investigated volume. Ground motion at these frequencies was found to be controlled by the main fractures observed at the site through numerical modeling and modal analysis. Both spectral analysis and cross-correlation of seismic noise showed short-period and seasonal reversible variations related to external air temperature fluctuations (Fig. 3). Numerical simulations revealed the essential key for the validation and interpretation of experimental results.

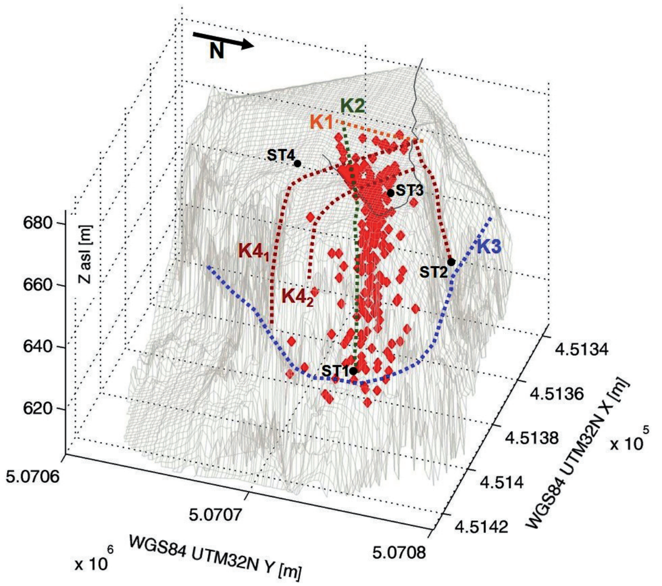

Fig. 2 – Microseismic event hypocentral location. Sources are located predominantly near K2 and K4 fractures.

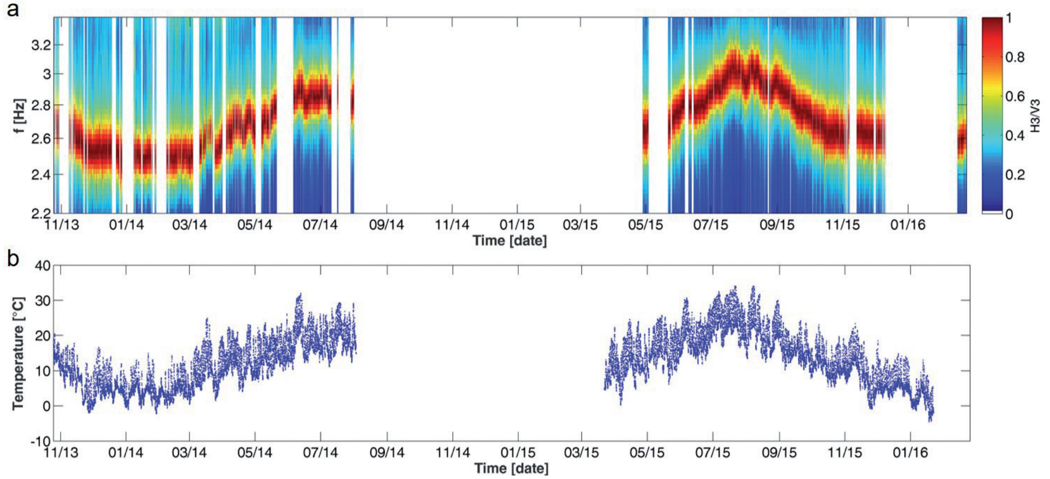

Fig. 3 – In a: temporal evolution (October 2013 - February 2016) of the first resonance frequency of the site, obtained with the Horizontal-to-Vertical Spectral Ratio method on ambient noise recorded at ST3 (at the top of the unstable sector A). Each spectral ratio is normalized to its maximum to follow the evolution of the peak in time. In b: air temperature monitored at the site in the same period. White time windows correspond to no available monitoring data.

Conclusions. The use of combined active characterization and passive seismic monitoring revealed successful in understanding the behavior of the potentially unstable cliff of Madonna del Sasso, overcoming the limitation of traditional geotechnical and remote-sensing monitoring techniques adopted in past years on the same site. No irreversible changes were detected during the monitored period. A strong thermal control was found to govern the stability of the cliff, with reversible seasonal opening and closing of fractures, resulting from thermal contraction and expansion, thus affecting the resonance frequency and the velocity field of the site. Moreover, microseismic events linked to these cycles of fracture opening/closing were detected, highlighting the dynamic activity of incipient fracturing of rock bridges and frictional sliding along fracture surfaces.

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