Seismic Monitoring of a Rockslide: The Torgiovannetto Quarry (Central Apennines, Italy)

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Abstract

A small-scale seismic network was deployed in the Torgiovannetto quarry (Central Apennines, Italy) from December 2012 to July 2013 to evaluate the possibility of improving the early-warning monitoring network of a rockslide by means of seismic observations. Four seismometers, acquiring data in continuous mode, were set up inside and at the edge of the quarry, with an average inter-station distance of about 100 m. The entire data set (7 months of recording) was analyzed through three different procedures: an STA/LTA (short-time-average /long-time-average) trigger, HVSR (Horizontal to Vertical Spectral Ratio and NCF (Noise-Correlation Function). The data analysis is still in progress. The preliminary data processing related to the identification and classification of recorded signals shows promising results but further refinements of the adopted algorithms are necessary in order to make this technique an helpful early warning tool. Extensive comparison and cross-analysis with parameters independently recorded by the other instruments of the monitoring network are necessary to reach the goals of the study.

272.1 Introduction

Landslides are a frequent and widespread geomorphological phenomenon that represent a severe threat to both people and facilities. Italy is one of the European countries most prone to landslides risk. Slope failure of rock masses represents an interesting case study for verifying the ability of passive seismic monitoring in order to detect: (a) signals related to micro-cracking; (b) signals related to rock blocks detachment and fall from the slope useful to reconstruct their associated trajectory; (c) possible variations in the elastic parameters of the rock body related to changes in pore-fluid pressure, consolidation, and micro-fracturing, which could forerun failure. The possibility of measuring such changes would thus constitute a significant improvement in our ability to forecast surface rock failure, and to mitigate the associated hazard. In this study, we describe a pilot experiment aimed at verifying the performance of a small-scale seismic network as a part of an early-warning system dedicated to an unstable rock mass monitoring. The test site is a dismissed limestone quarry located nearby the town of Assisi (Central Apennines, Italy) where a first rockfall and a subsequent reactivation occurred in 2003 (linked to the opening of the main fracture that we supposed to happen consequently to the 1997 earthquake) and in 2005 respectively (Fig. 272.1). In order to verify the performances of the detection and localization employed algorithm, we performed man-induced rock falls, then filming the blocks'

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Fig. 272.1 Location of the study area, Assisi (PG), Italy. Aerial photograph from Google Earth
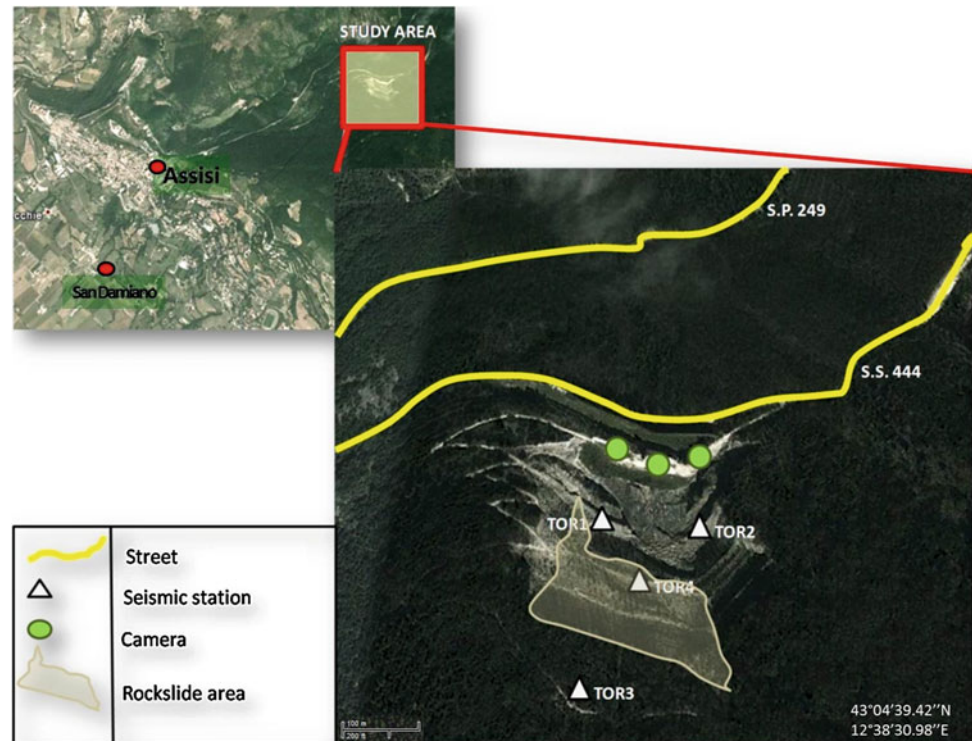
trajectories. The video recordings were taken by four high resolution cameras (two Canon EOS 600D, one Canon 660D and a Nikon D700; Fig. 272.1).

The rock fall trajectories were tracked on a geo-referenced Digital Terrain Model (DTM) through dynamic GPS measurements of the coordinates of initial and impact points of the blocks, using an algorithm implemented in Matlab. The final aim of this work was to automatically discriminate the signals related to the rock fall from the other recorded events (mainly earthquakes). Moreover, the acquired data were analyzed through the HVSR (Horizontal to Vertical Spectral Ratio; Nakamura 1989; Fäh et al. 2001) and NCF (noise-correlation function) techniques to verify the presence of parameters variation.

272.2   Torgiovannetto Rockslide

The Torgiovannetto rockslide (Fig. 272.1) is composed of regular stratifications of Jurassic-Cretaceous micritic limestone (locally known as Maiolica), with intercalations of thin, weak clay layers. The main front of the quarry is NW-SE oriented with an average dip of about 40°. The rockslide has a rough trapezoidal shape delimited by three main planes: a sub-vertical back fracture with an EW strike; the downhill boundary, represented by a stratigraphic layer (355°/24°), that acts as sliding surface and cuts obliquely the quarry front which is associated to a major clay interbed; the

western side of the landslide, delimited by fractures belonging to a sub-vertical discontinuity striking NS. The moving rock wedge has a calculated volume of about 1,82,000 m^3 and threatens two suburban roads which are the only connection between the town of Assisi and the surrounding villages; both roads are located close to the dismissed quarry.

272.3   Monitoring Network

The implemented small-scale seismic network is composed by four stations located inside or at the edge of the quarry, with an average inter-station distance of about 100 m (Fig. 272.1). Each station is composed by a SARA 24 bit digitizer, cable-connected to a tri-axial seismometer with a natural frequency of 4.5 Hz. Recorders acquire data in continuous mode, with a sampling rate of 200 samples/second/channel. Time synchronization at individual stations is achieved using the GPS time base. The experiment began on early December, 2012, and finished on July, 2013.

Since the installation of the four stations several hundreds events have been recorded. At present, the continuous data streams are analyzed using the following procedures: a) STA/LTA (short-term/long-term average) and b) cross-correlation function. The STA/LTA detection system individuates short-duration energy bursts. From the data analyzed thus far, it appears that most of the transient signals are associated with
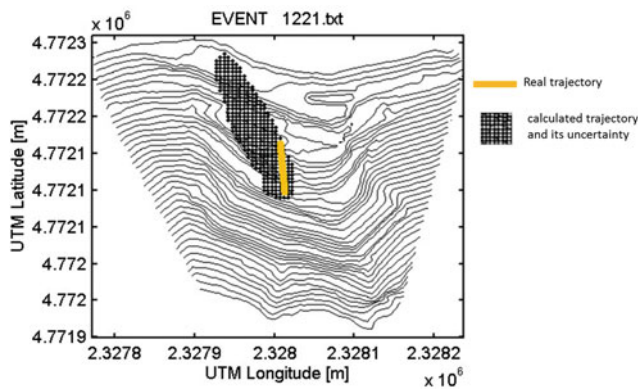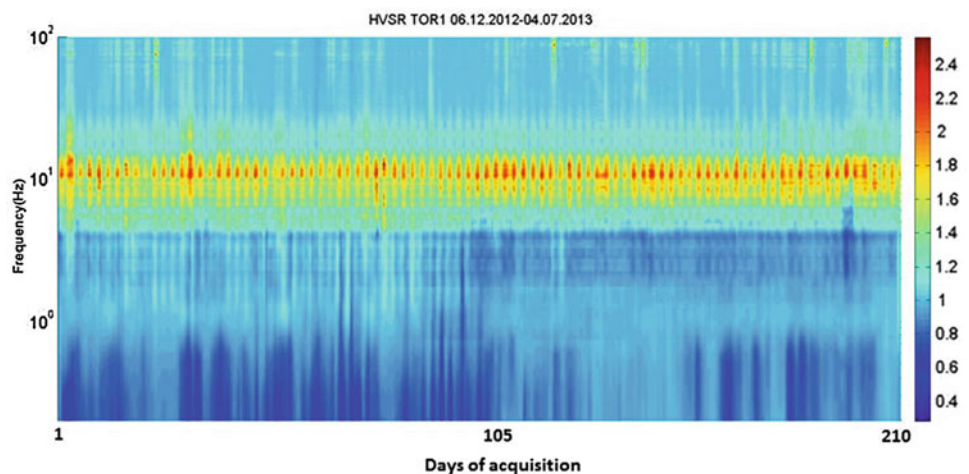
Fig. 272.2 On the right example of signals recorded by the four stations discriminated by the STA/LTA algorithm. On the left: reconstruction of the theoretical and real trajectory of a rock block fall

272.4   Data Analysis

Additional analysis were dedicated to the inspection of wave parameters which might reveal a degradation in the elastic properties of the rock mass. The failure of an unstable geological body is likely preceded by subtle changes in its elastic properties caused by variations in the stress state, fluid content, or both. As a consequence, the seismic velocity of the unstable mass would vary slightly, and such variations can be detected by a careful analysis of either earthquake or background noise seismic wavefields. At first, we computed the HVSR (Horizontal to Vertical Spectral Ratio), for 6-hour long time windows throughout the continuous recordings. Since the HVSR depends strictly on the profile of the shear-wave velocity (Vs), we do expect the former to track possible changes in the elastic parameters of the medium (Fig. 272.3).

In addition, we computed the noise correlation functions (NCF) among all independent pairs of receivers. Theoretical studies (Snieder 2004) have shown that, once averaged over long time intervals, the NCF at a pair of receivers approximates the Green's function between the two sites. The late portion (coda) of the NCF contains scattered waves, which have traversed the medium through much longer paths than those traveled by the direct (ballistic) arrivals. Therefore, coda waves are very sensitive to even tiny temporal changes in the seismic velocity of the medium they traveled through. In our application, the NCFs were calculated using 1-h-long time windows, and subsequently stacked over 1 day. Each newly-acquired daily correlogram is then tested against the stack of the previous ones in search of possible time shifts which could be indicative of a variation in the propagation velocity. This procedure, termed Coda Wave Interferometry (CWI; e.g., Pandolfi et al. 2006; Mainsant et al. 2012) is implemented by computing time-lapsed cross-correlation functions between the reference and test NCFs.

earthquakes (1 < M < 3) at local (<10 km) and regional (<100 km) distances. Additional work is needed in order to classify these events on the base of their waveform morphology, spectral content, and polarization properties, thus facilitating the discrimination of signals possibly related to brittle failure within the monitored rock mass. A further event discrimination/location procedure based on the windowed cross-correlation function among all independent pairs of signals, is currently under testing. In fact, the cross-correlation function attains a peak each time a coherent signal sweeps across the array, thus allowing its automatic detection. The time lags at which the correlation functions attain their peak values provide an estimate of the inter-station differential times, which can be used to locate the source of the signal (Saccorotti et al. this issue).

For locating the impact point of the rock blocks, we used a procedure based on the non-linear inversion of the seismic waves arrival time. For this analysis we assumed a constant rock velocity and sought for the minimum-misfit source over the gridded topographic surface (Fig. 272.2).

Fig. 272.3 Amplitude variation of the HVSR during the entire period of recording at TOR1

272.5 Discussion and Conclusions

The temporal analysis of the HVSR (Fig. 272.3) didn't highlight any first-order variation possibly associated with changes in the elastic parameters of the rock mass.

On the other side, data from the extensometric network and laser scanning surveys, indicate that ground displacement during the studied period was small and slow. Therefore, it is possible that such small movements have occurred aseismically, and without the involvement of any significant variation in the internal stress state of the rock mass. The location test performed using falling rocks indicates that the deployed network is able to provide a reliable estimate of the impact point of falling blocks. Location uncertainties are essentially related to (i) the approximate knowledge of ray trajectories within the unstable rock mass, and (ii) the scarce precision of the time-picking of the wave arrival times at individual stations. The study area is seismically active. Therefore, future efforts will be dedicates at the automatic discrimination of earthquakes form signals related to possible cracking phenomena within the unstable rock body. Though all the aforementioned analyses are performed offline, their implementation in a real time system is a straightforward task. More difficult is to establish reliable thresholds on individual parameters (e.g., rate amplitude of locally-sourced events, amount of seismic velocity changes) in order to use the whole processing framework as an early-warning tool. Achievement of this latter goal will require extensive comparison and cross-analyses with parameters independently recorded by the many other instruments currently operative at the monitored site.

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