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Seismometric Monitoring of Hypogeous Failures Due to Slope Deformations

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Abstract

Results from a seismometric monitoring of rock mass failures affecting a karstified slope are here presented. The slope, located in Central Apennines (Italy), hosts a drainage plant and is involved in gravity-induced deformations.

Starting from September 4, 2008 four accelerometric stations were installed within the tunnels of the drainage plant.

More than 1,000 events, referred to both earthquakes and hypogeous rock mass failures, were recorded.

The frequencies of occurrence of earthquakes and rock mass failures result to be generally well correlated; nevertheless, many hypogeous instabilities can be directly associated to the continuous slope deformations.

The trend of the cumulative Arias intensity derived for the hypogeous instabilities shows a time variable rate which was used as a tool for monitoring the deformational process of the slope as well as for managing the associated geological risk by the use of alert or alarm plans.

Keywords

Seismometric monitoring • Rock mass spreading • Hypogeous failures

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Introduction

Pre-failure behaviour of rock masses represents a complex geomechanical topic, since the existing stress conditions, the jointing conditions and the joint setting can strongly constrain pre-failure effects such as generation of new cracks, opening or closing of pre-existing joints and readjustment of the stress field within the rock mass. Recognizing pre-failure events by geological surveys as well as monitoring natural and anthropogenic systems is a major goal for the mitigation of risks due to the above mentioned "unexpected" and "rapid" events (Szwedzicki 2003). All the mentioned "failure precursors" can be monitored by use of specific devices.

In particular, the above mentioned transitional phase toward ultimate equilibrium conditions represents a useful chance to focus the process which is occurring, if a monitoring of the related events is performed.

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More complex scenarios of failure involving rock masses can be associated with impulsive triggers (i.e. explosions, collapses) or earthquakes. In these cases precursors do not necessarily occur, while the events representing possible triggers can be monitored.

Some experiments have been performed in mines or in landslide areas that were aimed at monitoring failure precursors by use of acoustic as well as seismometric devices (Lei et al. 2004, 2006; Deparis et al. 2008). On the other hand hypogeous instabilities triggered by impulsive events were recorded during experiments of controlled explosions and collapses of caves in mine areas (Miller et al. 1989; Phillips et al. 1997). Moreover, laboratory tests were performed on brittle materials to analyze possible correlations between acoustic emissions and observed microfracturing (Ganne et al. 2007).

Characteristic waveforms and frequency spectral features of microseismic emissions due to rock falls, collapses and explosions, both natural and artificially induced, were collected and analysed by many authors (Phillips et al. 1997; Heng 2009). On the whole, these studies proved that only a specific comparison among signals generated by different events (i.e. among natural events or among natural and artificial ones) allows a reliable discrimination.

The analysis of sequences of precursors as well as of post-failure events (i.e. hypogeous instabilities induced by impulsive triggers) can be considered a very useful tool for managing early warning, since monitoring the phases of failure propagation provides information on the changes which are involving the rock mass, but also on possible occurrence of more critical conditions (i.e. generalized collapse).

This study used a seismometric monitoring system to record precursors, post-failure events and triggering impulsive events within a karstified rock mass which hosts the major drainage system of Rome's aqueduct. The recorded sequences of the earthquakes as well as of the induced failures within the rock mass were analysed with the aim of evaluating possible trigger thresholds and recognising different levels of attention, based on the observed trends of events.

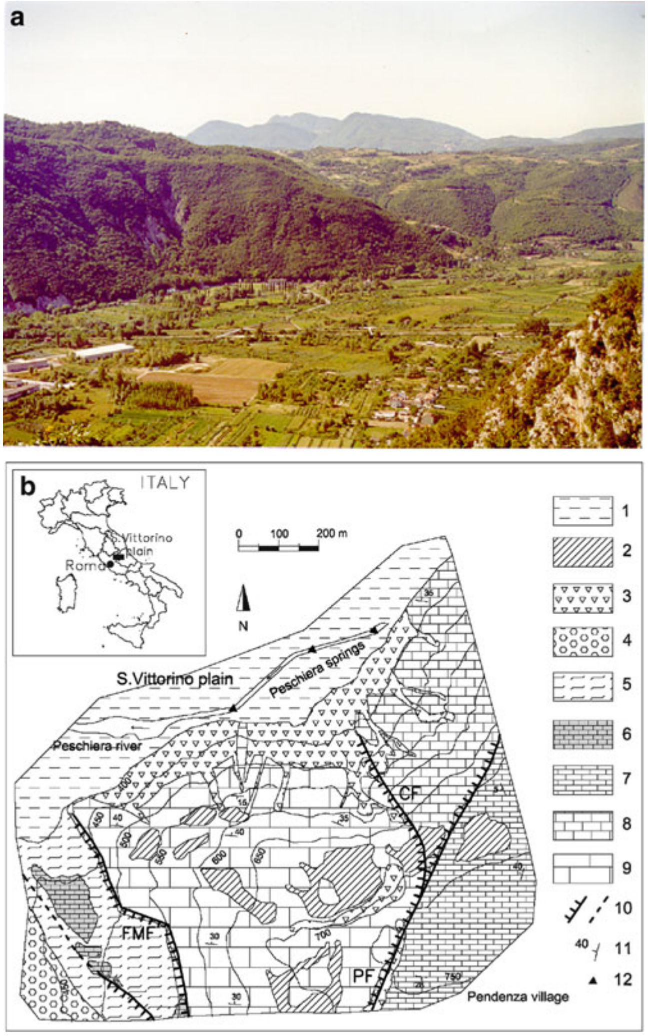

Fig. 1 Panoramic view from NE (**a**) and Geological sketch (**b**) of the Peschiera Springs slope: (*1*) Recent alluvial deposits of the Velino River; (*2*) Reddish soils; (*3*) Slope debris; (*4*) Gravel and conglomerate (upper Pliocene part–lower Pleistocene part); (*5*) Sandy-clayey flysch (upperMiocene); (*6*) Marly limestone (upper Cretaceous–lower Miocene); (*7*) Birdeyes micritic Limestone (lower Cretaceous); (*8*) Coral limestone (upper Malm); (*9*) Coral and echinids limestone (Malm part); (*10*) Fault (dashed if supposed): FMF Fiamignano-Micciani Fault, CF – Canalone Fault, PF – Pendenza Fault; (*11*) Strike and dip of strata; (*12*) Spring

Geological Setting of the Peschiera Spring Slope

The Peschiera Springs slope corresponds to the south-western flank of Mt. Nuria (Central Apennines, Italy) (Fig. 1) and is composed of limestones which belong to the Mt. Nuria unit (Ciotoli et al. 2001) and are ascrivable to the Malm part-Lower Cretaceous part interval.

The structural setting of the slope is monoclinic, with EW-trending and N-dipping (30–40 °) strata; many faults cross the slope with roughly NS and N35E trends (Fig. 1).

The slope also hosts a major karst aquifer which represents the drainage system of the Nuria-Velino-western Fucino and western Marsica (Velino-Sirente) mountains (total surface area: 1,016 km^2), whose main springs are the Peschiera-Canetra ones (measured total discharge: roughly 18–21 m^3/s; Boni et al. 1995).

Through geomorphological surveys as well as a recent digital, high-resolution (2 m), elevation model of the slope derived by a LIDAR (Light Detection And Ranging) remote survey, numerous gravity-induced morphological elements (e.g. scarps, trenches, sinkholes and tension cracks) were identified (Figs. 2 and 3). These landforms are indicative of

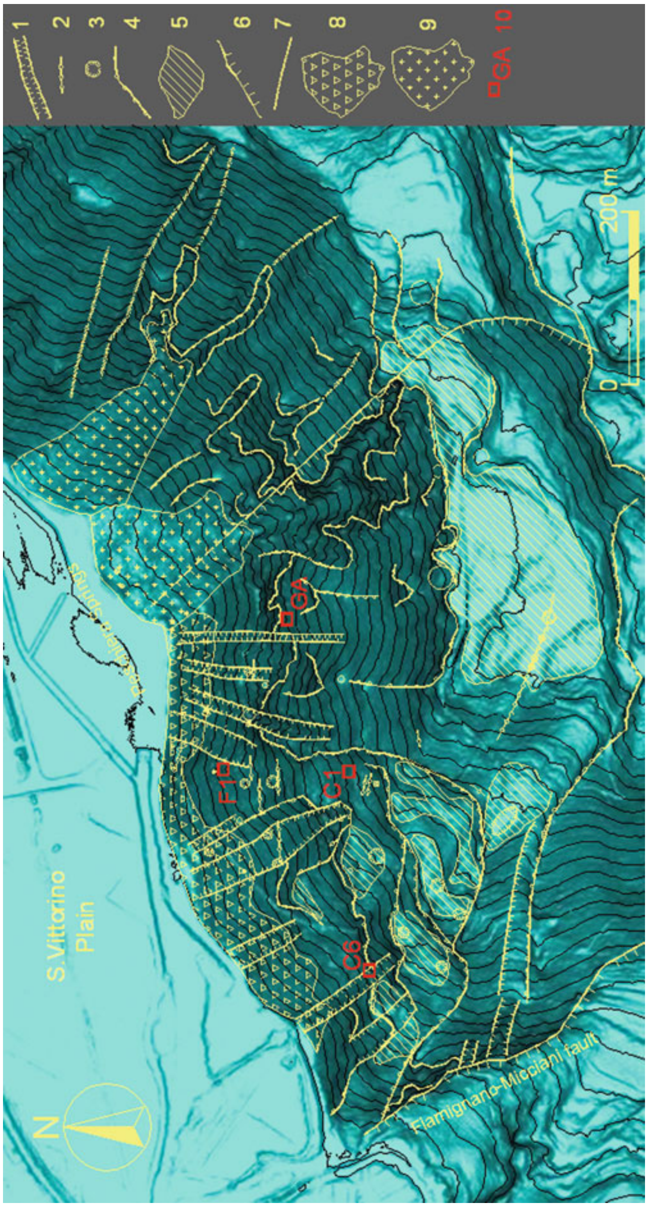

Fig. 2 Digital elevation model (DEM) from the LIDAR flight with geomorphological features. (*1*) Trench; (*2*) Tension crack; (*3*) Sinkhole; (*4*) Scarp; (*5*) Karstified flat; (*6*) Fault; (*7*) Gully; (*8*) Slope debris; (*9*) Debris fan deposit; (*10*) Accelerometric station within the drainage plant

slow, intense and pervasive slope deformations, which affect the entire slope and which correspond to various evolutionary stages ascribable to different portions of the slope, as proved by already published outputs of a stress–strain monitoring system installed within the drainage plant (Martino et al. 2004; Maffei et al. 2005).

Tens of sinkholes and depressions of variable size (diameter: 5 m to about 15 m; depth: 0.5 m to about 9 m) can be observed all along the slope; sometimes aligned along opened tension cracks.

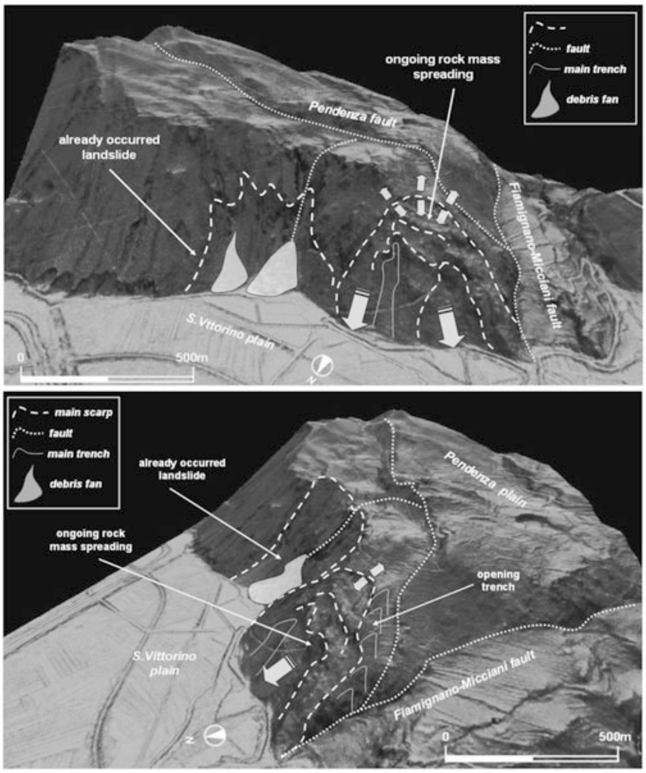

Fig. 3 3D views from the DEM of Fig. 2 showing the already occurred landslide and the ongoing rock mass spreading which involves the Peschiera Springs slope

Many scarps (with a height varying from 5 up to 15 m) are arranged both longitudinally and transversely to the slope.

All the collected geomorphological evidences enabled the recognition of three slope sectors with ongoing gravity-induced processes at different evolutionary stages (Martino et al. 2004; Casini et al. 2006): (1) a sector, including the southern portion of the slope and its top, with evidence of incipient, but limited deformation, in their early evolutionary stages; (2) a western sector, with evidence of mature, but not yet advanced evolution of gravity-induced deformations, where the major deformations are concentrated near the most marked gravity-induced elements and (3) an eastern sector, with evidence of advanced evolution characterised by pervasive deformation and pronounced gravity-induced elements, such as scarps, trenches and sinkholes.

The geological-evolutionary model of the slope reflects a complex deep-seated gravitational deformation, which initiates as a rock mass creep (Chigira 1992) and continuously evolves from a rock mass spreading to a rock-block mass deformation (Martino et al. 2004). In particular, the rock mass spreading can be clearly observed in the western portion of the slope (Fig. 3).

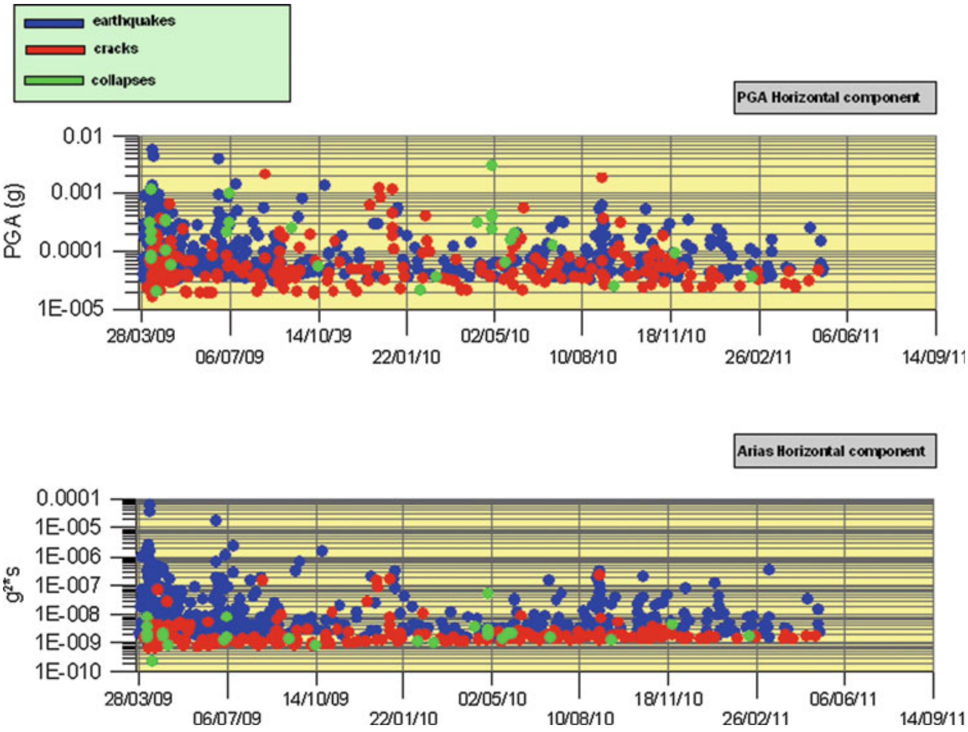

Fig. 4 PGA and Arias intensity (horizontal component – station C1) of all the events (earthquakes, cracks and collapses) recorded form March 2009 until May 2011

Seismometric Monitoring

Accelerometric Network

Starting from September 4, 2008 four accelerometric stations (GA, C1, F1 and C6 of Fig. 2) were installed by ACEA-ATO2 S.p.A. within the drainage plant of the Peschiera Springs in order to record both seismic events and hypogeous collapses. Each station was instrumented by a triaxial accelerometer (EPISENSOR KINEMETRICS) directly installed on bedrock. The four accelerometers were connected via cable to a digital data-logger (K2 KINEMETRICS) set to the absolute local time by a GPS device.

The monitoring system was managed by the Research Centre for Geological Risks (CERI) of the University of Rome “Sapienza” in order to properly set the recording device, analyze the collected data and suggest possible plans of management in case of a seismic crisis or a sequence of hypogeous events.

Two pass-band filters of the KINEMETRICS library (“classic strong motion” with a pass-band about 1–10 Hz and “IIRC” with a band-pass about 1–20 Hz) were alternatively applied to the channels of each station.

Moreover, some channels were set with a threshold trigger fixed according to their noise level, while others were set in STA/LTA (short time amplitude/long time amplitude) trigger mode, which is particularly devoted to the detection of low-magnitude earthquakes.

Recorded Data

Until the end of March 2009 only 7 events were recorded within the slope, but from April 2009, until May 2011 more than 1,000 events (about 800 earthquakes and 300 hypogeous instabilities) were recorded on the whole (Fig. 4).

To distinguish among different kinds of recorded events, a specific software was implemented through SAC (Seismic Analysis Code) and Fortran codes on Unix platform, taking into account the records obtained from the accelerometric network as well as the data collected by use of a temporary velocimetric array, which operated within the plant for about 5 months. The software allows to classify the events on the basis of their physical properties (i.e. energy, time duration, kinetic parameters and frequency content) and, in particular, to recognise among earthquakes, cracks and hypogeous collapses.

Magnitude and location of the recorded earthquakes were attributed according to the on-line data published by INGV (www.ingv.it).

The up to now recorded seismic sequences include the L’Aquila sequence, which started on March 28, 2009 and reached Mw 6.3 on April 6th and some seismic sequences from the M.nts Reatini seismogenetic area, which is about 30 km far from the Peschiera Spring plant and is characterized by intermediate-low magnitudes (i.e. up to 4.0).

Moreover, some far-field intermediate-high magnitudes earthquakes (i.e. higher than 5.0) were recorded, such as the Balcanic Peninsula, Southern Thyrrenian Sea, Japan (Lenti

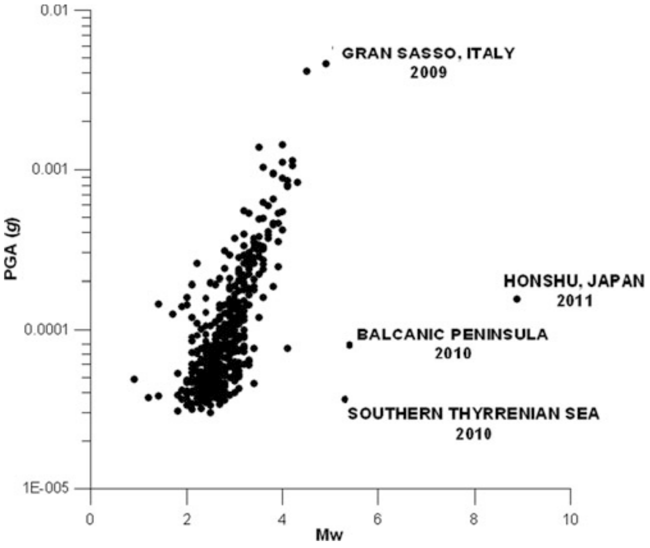

Fig. 5 PGA versus Mw for the earthquakes recorded from March 2009 until April 2011 by the Peschiera Spring accelerometric network

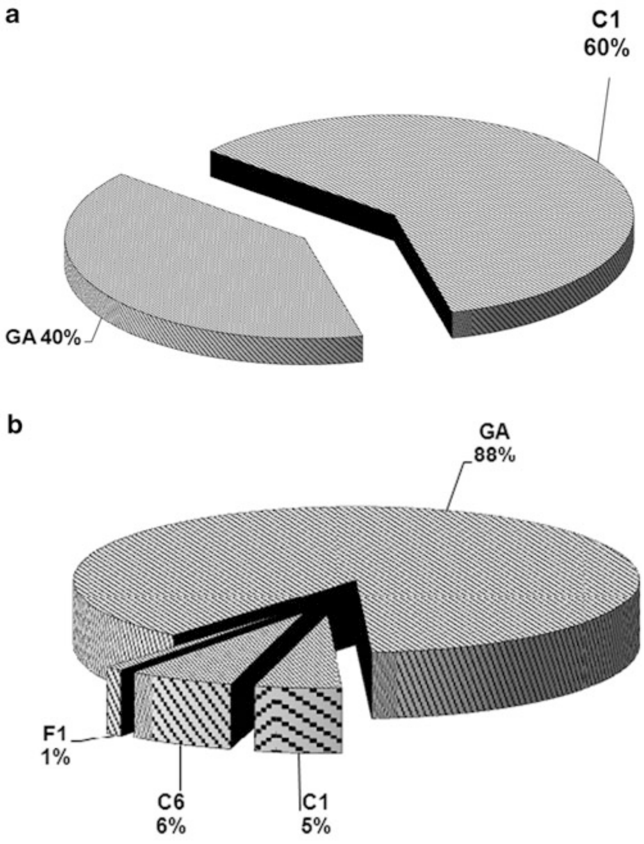

Fig. 6 (**a**) Distribution of the maximum PGA (horizontal component) at the recordings station referred to 30 recorded collapses; (**b**) distribution of the maximum PGA (horizontal component) at the recordings station referred to 270 recorded cracks

et al. 2011). The PGA and the Arias intensity values of the recorded earthquakes reach 0.1 m/s^2 and 10^{-4} g^{2}s respectively.

Taking into account the not seismic events the maximum average PGA related to the collapses (about 5.8 × 10^{-4} g) was obtained on the vertical component of C1 station, while for the cracks the maximum average PGA (about 2.6 × 10^{-4} g) was obtained on the horizontal components of GA station (Fig. 5), while the average Arias intensity obtained from the hypogeous events (i.e. both collapses and cracks) does not exceed 5.5 × 10^{-9} g^{2}s (horizontal component of GA station).

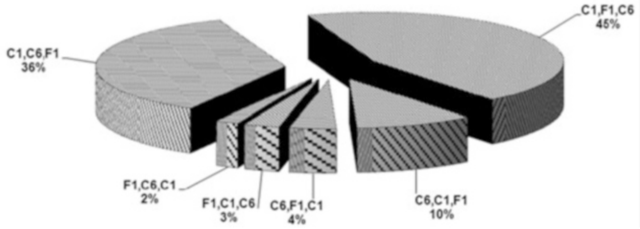

Fig. 7 Distribution of PGA attenuation respect to stations C1, F1 and C6, referred to the recorded crack events which were characterised by a maximum PGA at station GA (horizontal component)

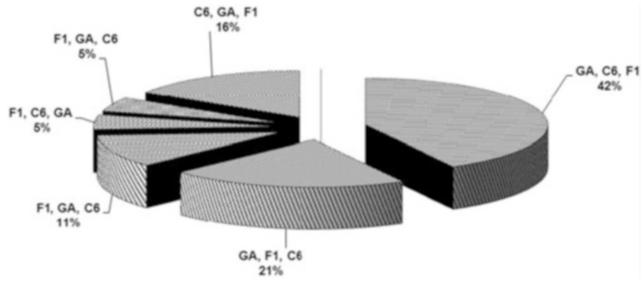

Fig. 8 Distribution of PGA attenuation respect to stations GA, F1 and C6, referred to the 30 recorded collapses which were characterised by a maximum PGA at station C1 (vertical component)

About 60 % of the recorded collapses show the maximum PGA at C1 station, on the vertical component of the motion, while the remnant 40 % at station GA (Fig. 6a). On the other hand, about 90 % of the recorded cracks show the maximum PGA at GA station and these maximum values are not associated to a specific component of the motion (Fig. 6b).

The time duration of the earthquakes is significantly greater (some tens of seconds) with respect to the not seismic events, since the cracks last some seconds and the collapses not exceed 1 s. Moreover, while the main frequency content of the earthquakes is limited to about 10 Hz, the cracks show a relevant frequency content up to 60 Hz and the collapses reach higher frequencies.

Based on the PGA spatial attenuation resulting from the network, the cracks are mainly located in the eastern portion of the slope and are mainly felt at stations GA and C1, while they are felt with a significantly reduced magnitude by the other stations, particularly by F1 station which is located very close to the external slope (Fig. 7). On the other hand, the collapses mainly occurred close to C1 station, which is located about 250 m far from the adjacent alluvial plain, and were mainly felt by GA station (Fig. 8).

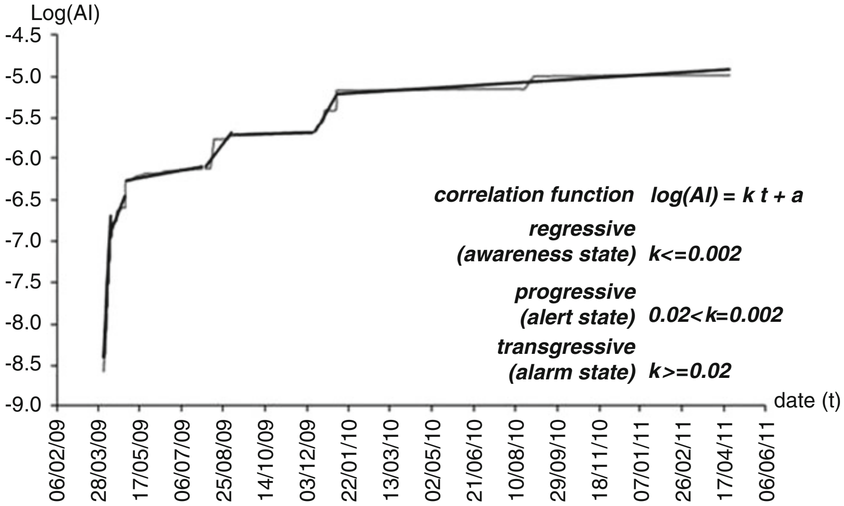

Fig. 9 Sequential analysis of the events recorded within the Peschiera Springs slope in the time interval 28 March 2009–25 April 2011. The time intervals are characterised by different trends of cumulative of Arias intensity (AI) and correspond to different attention levels for the management of the plant

Discussion

All the recorded collapses show maximum PGAs at station C1 or GA, while about 90 % of the crack events show maximum PGAs at station GA; these results are in good agreement with the evolutionary model of the deformational processes affecting the slope, which differentiates an eastern sector (station GA), characterised by an intensely jointed rock mass, and a western sector (station C1), where the highest deformations occur close to the main released rock mass bands, which correspond to a concentration of hypogeous caves (Maffei et al. 2005).

In general, the frequencies of occurrence of the seismic sequences and of the hypogeous instabilities are strongly correlated, even though many hypogeous instabilities can be associated to the continuous slope deformations since their frequency increasing cannot be directly related to seismic events. In this regard the hypogeous instabilities recorded during the April–May 2010 time interval are not related to any seismic event/sequence but they occurred some week before the Reatini M.nts sequence of September 2010.

In order to synthesise some features of the recorded dataset, the cumulative Arias intensity of the earthquakes and of the hypogeous instabilities was plotted versus time (Fig. 9).

This evidence suggests that different trends of increment of the cumulative Arias intensity can be derived from the above described plot. As an example, an increasing-rate trend was observed during the first 5 days after L'Aquila mainshock (i.e. until April 10, 2009); a constant-rate trend was observed during the following 3 weeks (i.e. until April 30, 2009); a decreasing-rate trend was observed in the following period (i.e. until the end of August 2009). Linear correlations were obtained for the logarithm of the cumulative Arias intensity vs. time in the before mentioned time intervals; these correlations correspond to angular coefficients (k in Fig. 9) which decrease of one order of magnitude per time interval down to 2×10^{-3}. These results are in good agreement with the monitoring of some indicators such as displacements, stresses, frequency of acoustic or microseismic emissions and magnitude of the emitted signals (Szwedzicki 2001, 2003), which can help to distinguish different trends associated to a decreasing, a stationary and an increasing hazard of failure and could be named as "regressive", "progressive" or "transgressive" respectively (Fig. 9).

The transgressive, progressive and regressive sequences of hypogeous instabilities referred to the hypogeous failures, which can be derived from the trend of cumulative Arias intensity, suggest different proceedings to manage the geological risk of the Peschiera Springs drainage plant; these proceedings have been referred to "alarm", "alert" and "awareness" levels of attention, which can be detected by transgressive, progressive and regressive sequences of hypogeous events respectively. In this regard, a more extended discussion and an upgrade of the recorded data was recently published by the Authors (Lenti et al. 2012).

Conclusion

The gravity-induced deformations involving the Peschiera Springs slope (Central Italy) are responsible for hypogeous instabilities within the rock mass. An accelerometric array, installed within the drainage plant of the Peschiera Springs (i.e. inside the slope), recorded about 800 earthquakes and about 300 not seismic events, including cracks and collapses, in about 30 months (September 2009–May 2011). The highest frequency of occurrence of the not seismic events was recorded immediately after the 6 April 2009 L'Aquila mainshock (Mw 6.3) (INGV, 2009).

On the other hand, many hypogeous instabilities can be associated to the continuous slope deformations since their frequency increasing cannot be directly related to seismic events/sequences.

Since the derived trend of cumulative Arias intensity referred to the hypogeous failures correspond to "transgressive", "progressive" and "regressive" sequences of such events, this detection drives to management proceedings, consisting in "alarm", "alert" and "awareness" levels of attention, which aims at mitigating the geological risk associated to the Peschiera Springs drainage plant.

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