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Seismic Monitoring of the Gravity-Induced Deformation Involving the Peschiera Spring Slope (Italy) for the Management of a Main Infrastructure

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ABSTRACT

The Peschiera Spring slope (Central Apennines, Italy), which hosts the tunnels of the main drainage plant of Rome aqueducts, is involved in a gravity-induced slope deformation. An average aquifer discharge of about 18 m^3/s is responsible for an intense limestone dissolution corresponding to the main kinematic elements that dislodge the jointed rock mass. Since 2008 a seismometric network was installed within the tunnels of the drainage plant for detecting local underground instabilities consisting of failures and collapses. About 1000 signals due to instabilities were recorded up to now. A control index (CI), based on both the frequency of occurrence and the cumulative energy of the recorded local instabilities was tested for providing three levels of alert. During the 2014 a total of 32 collapse crises were recorded, that caused several “emergency” states of the plant.

Introduction

The results presented in this work are part of a monitoring project of the Peschiera Springs slope, which hosts the main drainage plant of Rome aqueducts. This slope is affected by a gravitational deformation process consisting in a rock lateral spreading (Martino et al., 2004); the deformation mechanism has been characterized through the results of almost a decade of measurements obtained by a stress-strain monitoring system installed inside the tunnels of the plant (Lenti et al., 2012).

The pre-failure behavior of rock masses represents a complex geomechanical topic because the stress and jointing conditions as well as the joint setting can strongly constrain pre-failure effects, such as fractures generation, opening or closing of joints and readjustment of the stress field in the rock mass. Recognizing pre-failure events by geological surveys as well as by monitoring natural and anthropogenic systems is a major goal for the mitigation of risks due to the “unexpected” and “rapid” rock failure events (Szwedzicki, 2003). More complex scenarios of failure involving rock masses can be associated with impulsive triggers (i.e. explosions or earthquakes). In these last cases precursors do not necessarily occur, while the events representing possible triggers can be monitored.

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Some experiments have been performed in mines or in landslide areas with the aim of monitoring failure precursors by use of acoustic as well as seismometric devices (Deparis et al., 2008; Amitrano et al., 2010; Got et al., 2010). On the other hand hypogeous instabilities triggered by impulsive events were recorded during experiments of controlled explosions and collapses of caves in mine areas (Phillips et al., 1997).

The analysis of sequences of precursors and post-failure events (i.e. underground instabilities induced by impulsive triggers) can be considered a very useful tool for managing early preventive interventions, 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).

For this study, a seismometric monitoring system was used to record and analyze the collapses that affect the Peschiera Springs slope. This slope is involved in a rock mass creep process with a constant rate of deformation, in which internal and external factors (i.e. discharge variations and earthquakes) can increase the frequency of local instability events. During the year 2014 a total of 32 collapse crises were recorded into the rock mass that allowed to test an automatic event-detection procedure as well as to experience an alert system for the management of the plant. Indeed, a control index (CI) based on both the frequency of occurrence and the cumulative energy of the recorded local instabilities was tested for providing three levels of alert (“ordinary”, “alert” or “emergency”).

Geological Setting

The Peschiera Springs slope corresponds to the southwestern flank of Mt. Nuria (Central Apennines, Italy) and is composed of Malm-Lower Cretaceous limestones (Ciotoli et al., 2001; Bigi & Costa Pisani, 2002). The structural setting of the slope is monoclinic, with EW-trending and N-dipping (30°-40°) strata; many fault lines cross the slope with roughly NS and N35E trends.

The slope hosts a major karst aquifer which represents the drainage system of the Nuria-Velino-western Fucino and western Marsica mountains (total area: 1016 km^2), whose main springs are the Peschiera-Canetra ones (measured total discharge: roughly 18 to 21m^3/s according to Boni et al., 1986). The Peschiera Springs drainage plant, which consists of a complex system of drainage and collector tunnels and related connection halls, is part of Rome aqueducts managed by the ACEA-ATO2 S.p.A. Italian company.

Geomorphological surveys performed on the slope as well as a digital, high-resolution (2 m), elevation model of the slope (DEM), derived by a LIDAR (Light Detection And Ranging) radar remote survey, enabled to identify numerous gravity-induced morphological elements, e.g. scarps, trenches, sinkholes and tension cracks (Lenti et al., 2012). These landforms are indicative of slow, intense and pervasive deformations, which affect the entire slope. These deformations correspond to different evolutionary stages ascribable to specific portions of the slope, as proved by already published results from a stress-strain monitoring system installed within the drainage plant (Martino et al., 2004; Maffei et al., 2005).

In particular, it is possible to recognize three slope sectors with ongoing gravity-induced processes (Figure 1): I) a sector, including the southern portion of the slope and its top, with evidences of incipient and low deformations, i.e. in their early evolutionary stage; II) a western sector, with evidences of mature and not yet advanced gravity-induced deformations, only concentrated close to the main trenches or scarps and III) an eastern sector, with evidences of advanced gravity-induced slope deformations, characterized by pronounced landforms, such as scarps, trenches and sinkholes.

Figure 1. Digital elevation model (DEM) based on the LIDAR remote survey showing 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) Location of the rock fall of 22 March 2011; (11) Trace of the geological cross-sections; (12) Accelerometric station at the drainage plant; (13) Reference point for the azimuthal distribution of the time integral of the square velocity, derived from seismic noise records; (14) Velocimetric station for measuring seismic noise at the drainage plant; (15) Limits of the plant sectors (C6, C1, F1 and GA). Slope sectors (I, II and III) at different evolutionary stages are also shown. (from Lenti et al., 2012)

Seismometric Monitoring

Detection System

Since September 2008, four accelerometric stations (GA, C1, F1 and C6, see Figure 1) were installed in the Peschiera Springs drainage plant to record earthquakes and micro-seismic events, originated inside the slope and related to its gravitational dynamics. The accelerometric network, owned by ACEA-ATO2 S.p.A., is managed by the Research Centre for Geological Risk (CERI) of the Sapienza University of Rome in co-operation with the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) and the French Institute for Sciences and Technology for Transport, Development and Networks (IFSTTAR). Each station is equipped with a triaxial accelerometer (KINEMETRICS EPISENSOR) directly installed on bedrock, connected via cable to a 24-channel digital data-logger (KINEMETRICS GRANITE) which is set to the absolute local time through a GPS device and acquires with a 200 Hz sample frequency.

The trigger criteria of the data logger were set to record events characterized by different durations and large-band frequency content. At this aim, station C1 was set in the STA/LTA (short time amplitude/long time amplitude) trigger mode, which is devoted to the detection of low-magnitude earthquakes. The other stations were set with a threshold trigger fixed according to the local noise level (Lenti et al., 2012).

To distinguish among different kinds of recorded events, a specific script was implemented through SAC (Seismic Analysis Code) and Fortran codes on Unix platform, taking into account the records obtained from the accelerometric network (Lenti et al., 2012). The script provides a processing of the recorded accelerometric time-histories in both time and frequency domains to compute the following physical properties of the records: time duration, Fast Fourier Transform (FFT), Arias Intensity (AI) and Peak of Ground Acceleration (PGA). The script allows to classify events on the basis of their physical properties and, in particular, to recognize among earthquakes (near- and far-field seismic events focused outside the slope) and micro-seismic events originated within the slope. Among the latter, two types of events have been distinguished: failures related to rock-mass fracturing, with a duration from 1 to few seconds, and collapses, with a duration less than 1 second and a typical waveform of impact (Walter et al., 2012).

Alarm system

The analysis of the recorded events resulted to be a useful tool for managing the natural risk due to instabilities at the Peschiera Springs slope. At this aim, the frequencies of recorded earthquakes and micro-seismic events as well as the cumulative AI (Lenti et al. 2012) of the micro-seismic events are plotted as a function of time.

In order to provide an alarm system for the plant able manage the geological risk, a frequency index [FI(P, t)] was defined as the sum of an earthquake frequency index [FI_er(P, t)] and a micro-seismic events frequency index [FI_me(P, t)].

These indexes are daily assigned to each station according to the daily frequency of recorded events. Moreover, the rate of the cumulative AI of the recorded micro-seismic events was used to define for each station an energy index [EI(P, t)].

A final control index [CI(P, t)] is daily computed for each station of the network as a function of the sum of the frequency and energy indexes [FI(P, t)+EI(P, t)]. This last index enables the association of each specific sector of the plant (represented by the corresponding accelerometric station) with three possible levels of alarm: the “ordinary” level (OL) [CI(P, t)=1]; the “alert” level (AL) [CI(P, t)=2]; and the “emergency” level (EL) [CI(P, t)=3]. To take into account additional individual events of significant intensity, an alert threshold was fixed at a PGA value of 10^{-3} g based on the local PGA-magnitude curve (Lenti et al. 2012).

Recorded Data Analysis

Until December 2014, more than 2000 events were recorded by the accelerometric network: about 1000 earthquakes and 1000 events due to failures and collapses. In the 6 years of monitoring, a strong increase in the frequency of the micro-seismic events was observed since January 2014.

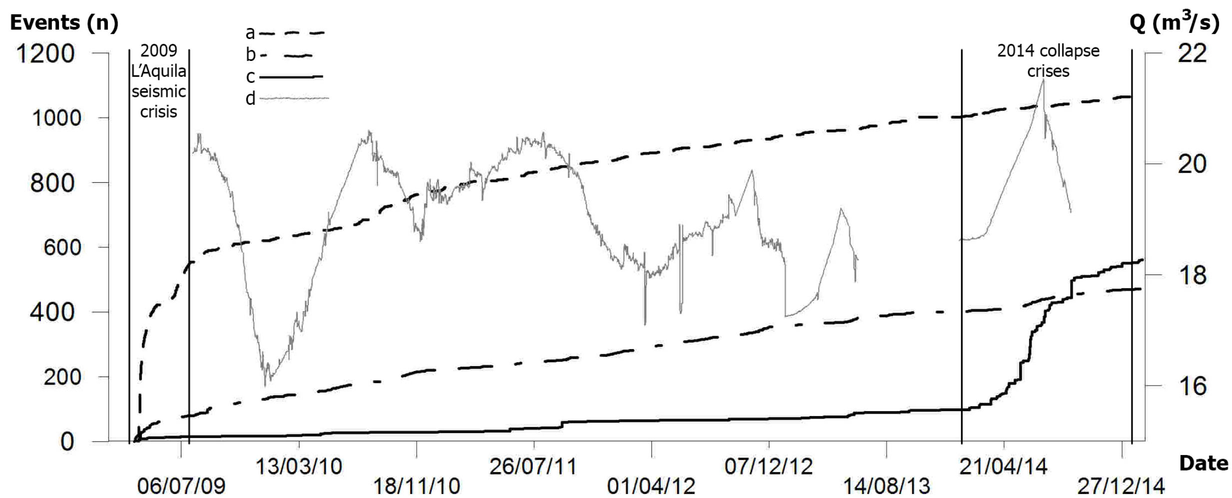

Figure 2. Cumulative trends of the recorded earthquakes (a), failures (b) and collapses (c) during the whole monitoring period (2008-2014). The daily total discharge is also shown (d), where the line is interrupted the data are not available.

About 50% of the micro-seismic events recorded in the whole period of monitoring (2008-2014) occurred in the last year. This is due to a strong increase of number of collapses recorded in the 2014 monitoring year. Furthermore, the earthquake induced phenomena can be always excluded, due to the absence of earthquake sequences before or during the collapse crises. This confirms that the gravitational dynamic generates deformational and paroxysmal events which can occur independently of external factors or actions.

Only five crises of collapses were observed in the period 2011-2013. These crises are characterized by the rapid succession of events, that follow one another in a period of time between few minutes and 1.5 hours. The lag between a collapse crisis and the next one varies from 110 to 356 days, with an average lag of 190 days. The source of the events is usually localized in the slope sector between the accelerometric stations GA and C1 (see Figure 1).

From January 2014 to December 2014 a sequence of 32 collapse crises characterized by a high frequency of events was recorded. In the 2011-2013 monitoring period only 96 collapses were observed, while in 2014 year 456 collapses were recorded. As reported in Figure 2, collapses recorded during 2014 show an anomalous trend if compared with the one of the previous years. It can be observed that this anomaly occurs simultaneously also in the maximum daily total discharge recorded during the whole monitoring period (2008-2014).

The 2014 crises are characterized by a high number of collapses concentrated in few hours or days. The lag between a collapse crisis and the next one is on average 10 days, with a variation from 2 to 35 days. Analyzing the recorded crises, the highest number of collapses was observed from 10 to 19 June 2014, when 90 collapses occurred in 10 days. Instead, 52 and 56 collapses throughout 2 days occurred during the crises from 25 to 26 May 2014 and from 10 to 11 September 2014 respectively.

The comparison among the acceleration peaks recorded at the four accelerometric stations points out that the collapses recorded during 2014 are localized in the slope sector nearby the C6 accelerometric station (Figure 1); the PGA values recorded in C6 are indeed about 2 orders of magnitude higher respect to the ones recorded in the other stations.

The PGA and the AI of the vertical component of the signals (PGA_v and AI_v respectively) are generally higher than the ones related to the horizontal components: the recorded events are, indeed, characterized by an average PGA_v of 10^{-3} m/s^2, with maximum of 10^{-2} m/s^2, and an average AI_v of 10^{-8} m/s, with maximum of 10^{-6} m/s. Figure 3 reports the PGA_v and AI_v values of the most energetic event for each collapse crisis; as it results, from the 2014 database, the collapse crises are placed in a lower-middle field of PGA_v vs AI_v referred to the 2011-2013 time interval. An exception can be observed during the 23-24 March 2014 crisis when a collapse characterized by particularly high values of PGA_v and AI_v (2.00×10^{-2} m/s^2 and 2.36×10^{-6} m/s respectively) was recorded.

Attention levels

During the 2014, the CI(P, t) computed in the sector of the plant referable to the C6 station reached the “ordinary” level for 201 days, the “alert” level for 72 days and the “emergency” level for 49 days. Instead, the sector of the plant referable to the C1 station reached the “ordinary” level for 163 days, the “alert” level for 112 days and the “emergency” level for 47 days. In the sector of the plant referable to the GA station the “ordinary” level was reached for 170 days, the “alert” level for 127 days and the “emergency” level for 25 days. Finally, the sector of the plant referable to the F1 station reached the “ordinary” level for 151 days, the “alert” level for 154 days and the “emergency” level for 17 days (Figure 4).

As it results from the aforementioned data, in the sector of the plant referable to the C6 sector, where the collapse crises were localized, the “emergency” level was reached more times than in the other sectors of the plant. The high frequency of occurrence of the collapse crises, mainly localized in the C6 slope sector causes an instantaneous shift of CI(P, t) from “ordinary” to “emergency” state, according to the current alarm system.

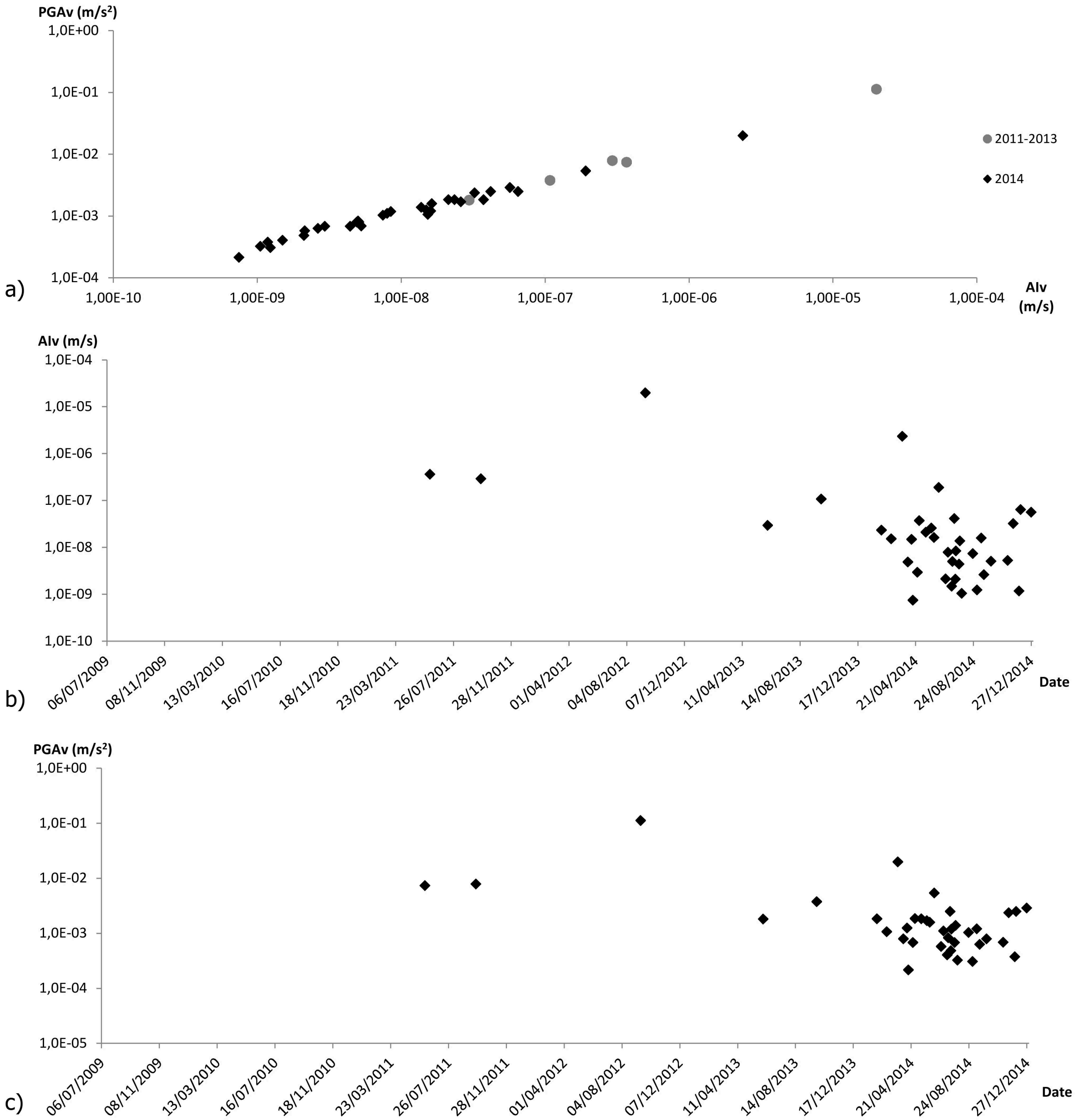

Figure 3. a) PGA_V vs AI_V obtained for the most energetic collapse recorded by the accelerometric network for each collapse crisis; b) AI_V vs time of the most energetic collapses for each crisis; c) PGA_V vs time of the most energetic collapses for each crisis.

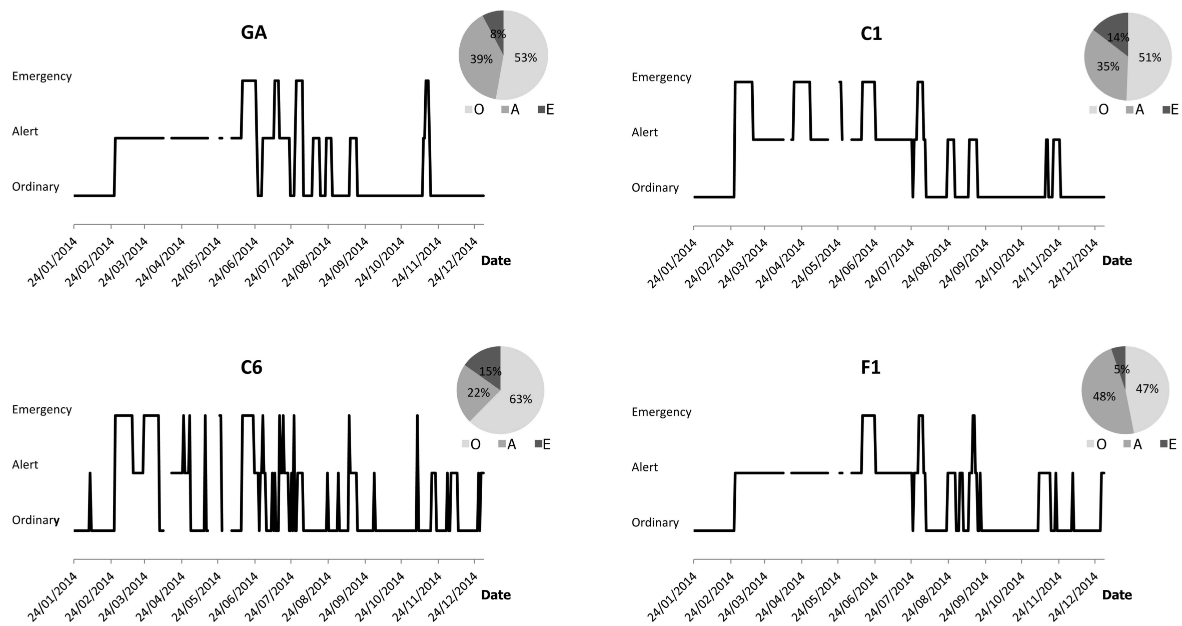

Figure 4. Daily C(P,t) attributed to each slope sector (C1, C6, F1 and GA) during the 2014 and respective aerograms, in which “O” indicates the percentage of “ordinary” level, “A” of “alert” level and “E” of “emergency” level; where the line is interrupted the data are not available.

Conclusion

The gravity-induced deformations involving the Peschiera Springs slope (Italy), where a Rome aqueducts drainage plant is located, cause underground instabilities that affect the rock mass. Since September 2008 an accelerometric network has been operating in the drainage plant.

During six years of monitoring, the network recorded more than 2000 events. An analysis of some physical features of the records (i.e. time duration, PGA and AI) enabled the recognition of different types of events, such as earthquakes focused outside the slope and micro-seismic events (failures and collapses) focused within the slope.

Starting from the analysis of the recorded events, a warning system was developed for the Peschiera Springs drainage plant. This system allows to associate a level of alarm (“ordinary”, “alert” and “emergency”) to different sector of the plant. The level of alarm determines different procedures to manage the geological risk related to the ongoing gravitational instabilities of the slope.

From January 2014 to December 2014 a sequence of 32 collapse crises was recorded. These crises are characterized by a high frequency of event occurrence having a low level of PGA and AI. It was observed that the C6 sector, where the collapse crises were located, has reached the “emergency” level more frequently respect to the other sectors.

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