DOI: 10.4408/IJEGE.2013-06.B-14

MICROSEISMICITY RELATED TO GRAVITY-INDUCED SLOPE DEFORMATIONS FOR RISK MANAGEMENT

LUCA LENTI(*), SALVATORE MARTINO(**), ANTONELLA PACIELLO(***), ALBERTO PRESTININZI(**) & STEFANO RIVELLINO(**)

(*) Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR-Paris)
(**)Sapienza Università di Roma - Dipartimento di Scienze della Terra e Centro di Ricerca CERI - Rome, Italy
(***)Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile (ENEA) - C.R. Casaccia - Rome, Italy

ABSTRACT

An accelerometric array installed on 4 September 2008, has been used to manage the geological risk in the Peschiera Springs drainage plant of Rome's aqueduct, located in the Central Apennines approximately 80 km from Rome, Italy. The plant occupies a carbonatic slope that is extensively involved in gravitational deformations, which are responsible for underground failures such as cracks and collapses of karst caves. To distinguish among different types of recorded events, an automated procedure was implemented taking into account duration, peak of ground acceleration (PGA) and its variation within the accelerometric array. The main sequence of underground failures so far recorded was related to the L'Aquila seismic sequence occurred in April 2009. Moreover, a very intense sequence of underground failures occurred in September 2011 that was not related to seismic events, i.e. only due to the gravitational processes affecting the slope. These evidences prove that the ongoing gravitational slope deformations have a key role in predisposing and/or causing the underground failures within the karst rock mass of the Peschiera Spring slope.

A control index (CI) is daily computed as a function of sub-indexes which are derived from the rate of cumulative Arias intensity of underground failures, the frequency of underground failures and the frequency of earthquakes. The CI index identifies "ordinary", "alert" or "emergency" levels of attention and represents a fundamental tool for managing the geological risk associated with the deformational process affecting the drainage plant.

KEY WORDS: gravity-induced slope deformations, displacement monitoring, micro-seismicity, warning system

INTRODUCTION

This study used an accelerometric array to record precursors, post-failure events and triggering impulsive events within a karst rock mass hosting the major drainage system of Rome's aqueduct. Seismic and microseismic recorded events were compared with the data obtained by a stress-strain monitoring system installed inside the slope, to analyse the detected deformations in relation to both the ongoing gravitational process and the external forcing (i.e. earthquakes). In this regard, since the 70s' the influence on entire slopes of the inertial forces due to the interaction of long or very-long period dynamic actions (such as tides or teleseismic earthquakes) was worldwide demonstrated in relation to volcano activity, volcano-tectonic flank deformations (JOHNSTON & MAUK, 1972; MCNUTT & BEAVAN, 1984; RYDELEK *et alii*, 1988; KASAHARA, 2002; MIYAZAWA *et alii*, 2005; SOTTILI *et alii*, 2007) and recently to interplate slow slip event (ITABA & ANDO, 2011).

On the other hand, the pre-failure behaviour of rock masses represents a complex geomechanical problem because the stress and jointing conditions as well as the joint setting can strongly constrain pre-failure effects, such as generation of cracks, opening or closing of joints and readjustment of the stress field within the rock mass. All of these failure precursors can be monitored by specific devices. However, on-going geological and geomechanical deformation, which can proceed from a transitional phase to rock-mass failure at yielding conditions, is indicative of the proneness of a rock mass to further deformation or failure (Szwedzicki, 2003). 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. 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 (Miller *et alii*, 1989; Lei et *alii*, 2004; Lai *et alii*, 2006; Paskaleva *et alii*, 2006; Deparis *et alii*, 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 (Phillips *et alii*, 1997; Yang *et alii*, 1998). Many authors (Miller *et alii*, 1989; Phillips *et alii*, 1997; Heng, 2009) have analysed spectral features of microseismic emissions due to rock falls, collapses and explosions, both natural and artificially induced, distinguishing specific signal features for different types of events.

The analysis of sequences of precursors as well as of 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).

The monitoring system installed within the Peschiera Spring slope is also devoted to evaluate possible trigger thresholds or to recognise different levels of attention, based on the observed trends (specifically in terms of frequency and energy) of events; in this way, it represents a remarkable risk management tool for the drainage plant.

THE PESCHIERA SPRING SLOPE

GEOLOGICAL SETTING

The Peschiera Springs slope corresponds to the south-western flank of Mt. Nuria (Central Apennines, Italy) and it is composed of Malm - Lower Cretaceous limestones (Capotorti *et alii*, 1995; Ciotoli *et alii*, 2001; Bigi & Costa Pisani, 2002) (Fig. 1). 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 (Fig. 1).

The slope 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: 1016 km^2), whose main springs are the Peschiera-Canetra ones (measured total discharge: roughly 18 to 21 m^3/s according to Boni *et alii*, 1986; Boni *et alii*, 1995). The Peschiera Springs drainage plant, which consists of a complex system of drainage and collector tunnels and related connection halls, is part of the Rome aqueduct system managed by the ACEA-ATO2 S.p.A. Italian company

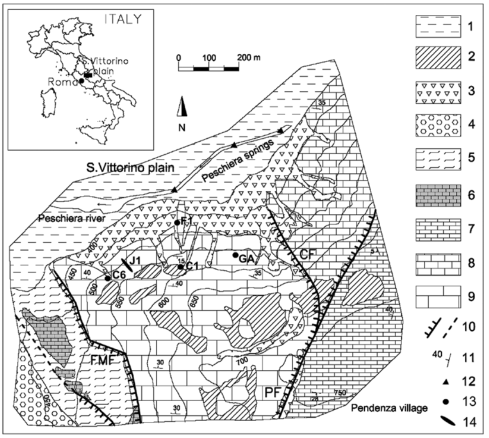

Fig. 1 - Location and geological sketch of the Peschiera Springs slope: (1) Recent alluvia of the Velino River; (2) Reddish soils; (3) Slope debris; (4) Gravel and conglomerate (upper-Pliocene and lower- Pleistocene parts); (5) Sandy-clayey flysch (upper Miocene); (6) Marly limestone (upper Cretaceous–lower Miocene); (7) Birdseye micritic limestone (lower Cretaceous); (8) Coral limestone (upper Malm); (9) Coral and echinoids limestone (Malm part); (10) Fault (dashed if estimated): FMF Fiamignano-Micciani Fault, CF Canalone Fault, PF Pendenza Fault; (11) Strike and dip of strata; (12) Springs; (13) accelerometric station installed within the drainage plant; (14) monitored joint within the drainage plant

ONGOING GRAVITATIONAL SLOPE DEFORMATION

Geomorphological surveys performed on the slopes 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) (Fig. 2) (Lenti *et alii*, 2012). These landforms are indicative of slow, intense and pervasive slope 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 outputs of a stress-strain monitoring system installed within the drainage plant (Martino *et alii*, 2004; Maffei *et alii*, 2005). More in particular, it is possible to recognise three slope sectors with ongoing gravity-induced processes (Martino *et alii*, 2004): 1) a sector, including the southern portion of the slope and its top, with evidence of incipient and low deformations, i.e. in their early evolutionary stage; 2) a western sector, with evidence of mature and not yet advanced gravity-induced deformations, only concentrated close to the main trenches or scarps and 3) an eastern sector, with evidence of advanced gravity-induced slope deformations, characterised by pronounced landforms, such as scarps, trenches and sinkholes.

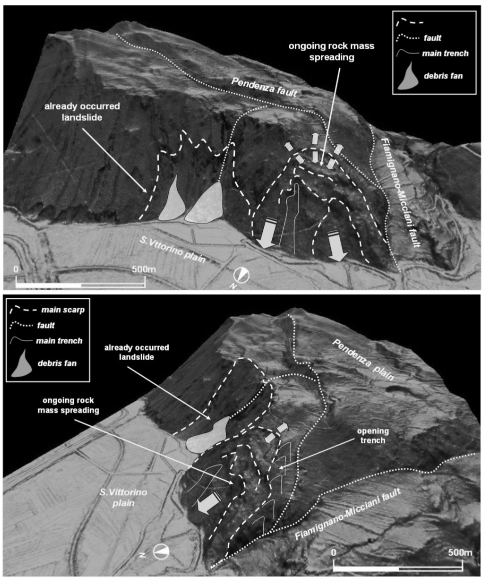

Fig. 2 - 3D views of the DEM showing the already occurred landslide and the ongoing rock mass spreading which involves the Peschiera Springs slope

The geological-evolutionary model of the slope reflects a complex deep-seated gravitational deformation, which initiates a "sackung" phenomenon (Zischinsky, 1969; Savage & Varnes, 1987) continuously evolving from rock-mass spreading (Hutchinson, 1988) to rock-block mass deformation (Martino *et alii*, 2004). In particular, the rock-mass spreading can be clearly observed in the western portion of the slope, where it is associated to a radial displacement field and it generates continuous transversal scarps combined to longitudinal trenches (i.e. multiple transversal trenches).

MONITORING SYSTEM

DISPLACEMENT MONITORING

A geotechnical monitoring system was installed, from September 2007, inside the Peschiera Springs slope to detect the continuous gravitative deformations which involve the mass rock. This monitoring system consist in:
- 8 strain-gauge installed on structural reinforcements
- 7 line extensometers
- 14 uniaxial distantiometers
- 15 triaxial distantiometers

These devices were installed within the tunnels of the Peschiera Spring drainage system to detect stress-strain effects on structural elements and cracks on both the exposed rock and the tunnel cover. All the sensors have a displacement resolution of 0.1 μm and automatically record at time intervals of 1 hour. The recorded data are collected by a local data-logger which enables a remote download; the downloaded data are automatically processed to return a monitoring report.

ACCELEROMETRIC MONITORING

Starting from 4 September, 2008 four accelerometric stations (GA, C1, F1 and C6 of Fig.1) were installed by ACEA-ATO2 S.p.A. within the drainage plant of the Peschiera Springs in order to record both seismic events and underground 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 underground events. Until November 2012 more than 1300 events (about 950 far and near earthquakes and 400 underground instabilities) were recorded on the whole.

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 (LENTI *et alii*, 2012). 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 (micro-earthquakes) and underground collapses. The physical properties of the recorded waveforms are analysed in the time domain, and the PGA variation among the recording stations is also considered by the use of a percentage PGA-variation index (VI) which has been defined in the form:

VI=((PGAmax–PGAaverage)/PGAaverage))*100

The different types of events are actually distinguished by using PGA, VI and time duration values according to the scheme of Fig. 3.

OBSERVED DEFORMATIONAL EPISODES

Since 2009 several deformational episodes were observed by the monitoring system within the Peschiera Spring slope; among these episodes it is possible to distinguish the following typologies:

1. deformational effects clearly related to external actions such as near field seismic sequences and teleseismic earthquakes;
2. deformational effects related to local micro-seismic sequences and corresponding to cracks or collapses occurred within the slope;

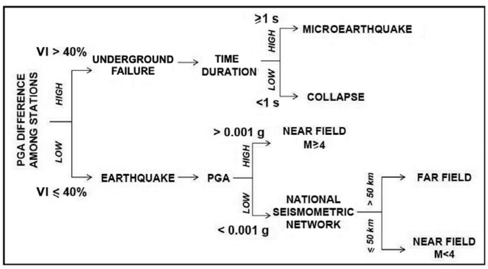

Fig. 3 - Flowchart showing the detection procedure adopted to distinguish different types of events recorded by accelerometric network within the Peschiera Springs slope

3. deformational effects which were not related to seismic records.

Examples of the first typology of deformational episodes were obtained: i) during the near field (epicentral distance of about 30 km) L'Aquila seismic sequence (Fig. 4), started with the Mw 6.3 mainshock occurred on 6 March 2009 at 3.32 a.m. and ii) during the 11 March 2011 Japan earthquake (Mw 8.9) (Fig. 5), which was recorded as a teleseismic event by the Peschiera Spring accelerometric array. In these cases a maximum displacement up to 0.3 and 0.7 mm was respectively recorded within the drainage plant along the monitored joints; these displacements were reached in about one week from the triggering seismic event. A similar behaviour, was observed in the case of the 23 December 2008 Frignano (Mw 5.1) earthquake and in the case of the 15 January 2009 Kuril Islands (Mw 7.3) earthquake; nevertheless, in this case maximum displacements up to 2 mm were instantaneously recorded after the seismic shaking. Moreover, the July 2009 Mts Reatini seismic sequence and the 12 July 2009 earthquake (Mw 4.0) from L'Aquila district (epicentral distance of about 25 km), triggered a deformational event responsible for a maximum recorded displacement along the monitored joints up to 3.5 mm (Fig. 6).

An example of the second typology of deformational episodes was obtained during the 13 September 2012 micro-earthquake sequence with a time duration of ten of minutes and due to underground collapses of karst caves within the slope; this event was responsi-

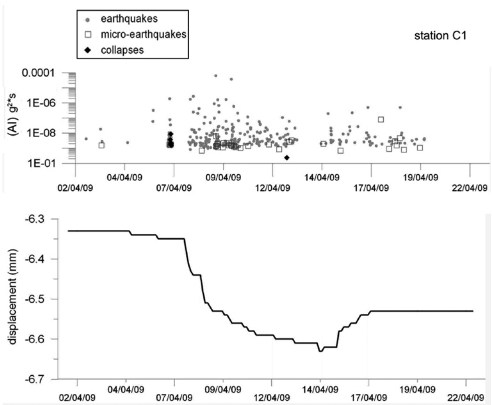

Fig. 4 - Computed horizontal Arias intensity for the recorded seismic and micro-seismic events (up) and displacement monitored within the Peschiera Spring drainage plant (point J1 of Fig. 1): the time window shows the L'Aquila seismic sequence started on April 2009 with the Mw 6.3 mainshock

ble for a maximum recorded displacements up to 0.3 mm in few hours (Fig. 7).

Many examples of the third typology of deformational episodes are given by sudden displacements (up to 2.8 mm) recorded along the monitored joints which cannot be related to any seismic or micro-seismic sequence (Fig. 8).

It is worth noting that all the above reported deformational episodes, observed along the monitored joints, represent significant strain effects if compared to the average strain-rates recorded within the slope which are in the order of few mm/year (i.e. up to 5 mm/year).

WARNING SYSTEM

The analysis of the recorded events is a useful tool for managing the natural risk due to underground failures at the Peschiera Springs drainage plant. For this purpose, the frequencies of the earthquakes and underground failures as well as the cumulative Arias intensity of the underground failures are plotted as a function of time.

To provide an alarm system for the plant in the case of underground events, a frequency index (FI(P,t)) was defined as the sum of an earthquake frequency index (FI_er(P, t)) and a micro-earthquake fre-

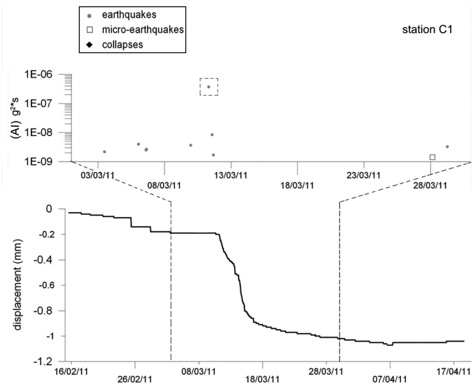

Fig. 5 - Computed horizontal Arias intensity (AI) for the recorded seismic and micro-seismic events (up) and displacement monitored within the Peschiera Spring drainage plant (point J1 of Fig.1): the time window shows the 11th March 2011 Japan earthquake (Mw 8.9 - dashed envelope)

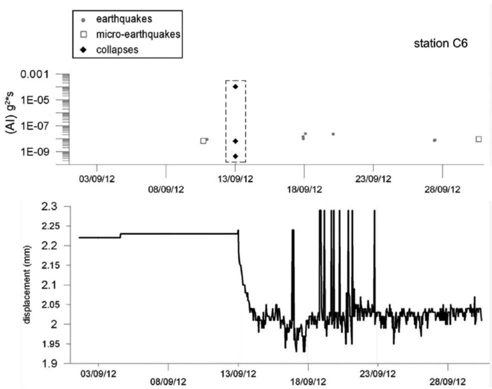

Fig. 7 - Computed horizontal Arias intensity (AI) for the recorded seismic and micro-seismic events (up) and displacement monitored within the Peschiera Spring drainage plant (point J1 of Fig.1): the time window shows the micro-earthquake sequence due to underground collapses (dashed envelope) occurred on 13 September 2012

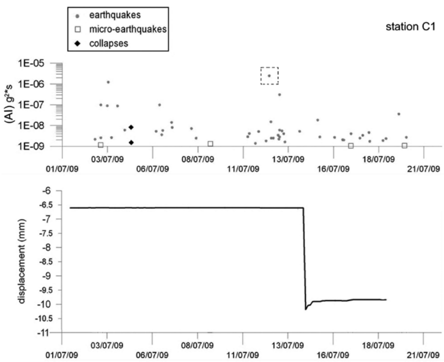

Fig. 6 - Computed horizontal Arias intensity (AI) for the recorded seismic and micro-seismic events (up) and displacement monitored within the Peschiera Spring drainage plant (point J1 of Fig.1): the time window shows the Mts Reatini seismic sequence on July 2009 followed by the 12 July 2009 earthquake from L'Aquila district (Mw 4.0 – dashed envelope)

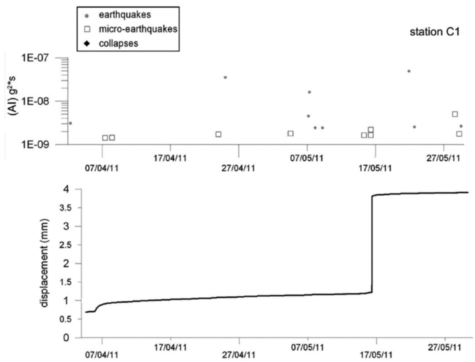

Fig. 8 - Computed horizontal Arias intensity (AI) for the recorded seismic and micro-seismic events (up) and displacement monitored within the Peschiera Spring drainage plant (point J1 of Fig.1): the time window shows a sudden displacement recorded on 16 May 2011 and not triggered by earthquake or micro-earthquake sequences

Earthquake frequency (event/day)	Micro-earthquake frequency (event/day)	FI_er/me(P,t)
0-10	0-3	0
11-20	4-10	1
>20	>10	4
Energy rate (g^2)		**EI(P,t)**
$\leq 10^{-3}$		0
$10^{-3}/10^{-2}$		1
$\geq 10^{-2}$		4
Alarm level	**FI(P,t) + EI(P,t)**	**CI(P,t)**
Ordinary	0	1
Alert	1-3	2
Emergency	4-12	3

Tab. 1 - Values of the Indexes used for evaluating the alarm levels within the Peschiera Spring drainage plant

quency index (FI_me(P, t)).

These indexes are daily assigned to each station according to the daily frequency of recorded events (Tab. 1). Moreover, based on the previously described rate of cumulative Arias intensity of the recorded micro-earthquakes, an energy index (EI(P,t)) is attributed to each station (Tab. 1).

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 derived thus far (Lenti *et alii*, 2012).

According to the above described warning system, in the total period of monitoring, the "alert" level was reached 7 times, due to seismic or micro-seismic sequences, while the "emergency" level was reached only twice: i) during the near field L'Aquila seismic sequence on April 2009 and ii) during a local the micro-seismic sequence associated to collapses on September 2011.

CONCLUSIONS

The integrated stress-strain and accelerometric monitoring systems installed within the drainage plant of the Peschiera Spring slope recorded many interesting deformational episodes which can be related to the ongoing gravity-induced instability affecting the slope sometimes associated to micro-earthquake sequences due to underground failures (i.e. collapses and cracks) as well as to the interaction of the slope with external actions, such as seismic or teleseismic events. Based on the monitoring data it is possible to remark that significant displacements (i.e. up to few millimetres) can occur suddenly or within a week-time as an effect of external actions, if compared, with the average recorded strain rate, i.e. up to 5 mm/years. The installed accelerometric array is presently devoted to a remote-controlled warning system which returns, to the manager of the drainage plant, "alert" or "emergency" levels, so providing a mitigation of the geological risk related to the ongoing gravitational instabilities of the slope.

ACKNOWLEDGEMENTS

The Authors wish to thank Dario Rinaldis and Carlo Romagnoli for the scientific discussions on the findings. Thanks also to ACEA-ATO2 S.p.A. and to Giorgio Martino for the technical support to this study. The research was carried on in the frame of the Convention between CERI and ACEA-ATO2 S.p.A. for the study of the gravitational processes affecting the Peschiera Spring slope, (Project leader: Prof. Alberto Prestininzi).

REFERENCES

Bigi S. & Costa Pisani P. (2002) - *Structural setting of the Cicolano-M. Calvo area (Central Apennines, Italy)*. Bollettino Società Geologica Italiana Speciale, **1:** 141-149.

Boni C.F., Bono P. & Capelli G. (1986) - *Schema idrogeologico dell'Italia Centrale*. Memorie Società Geologica Italiana, **35**: 991-1012.

Boni C.F, Capelli G. & Petitta M. (1995) - *Carta idrogeologica dell'alta e media Valle del F. Velino*. Elaborazione cartografica e stampa System Cart, Roma.

Capotorti F., Fumanti F. & Mariotti G. (1995) - *Evoluzione tettonico-sedimentaria e strutturazione del settore di piattaforma carbonatica laziale-abruzzese nell'alta Valle del F. Velino*. Studi Geologici Camerti Speciale, **2**: 101-111.

Ciotoli G., Di Filippo M., Nisio S. & Romagnoli C. (2001) - *La Piana di S. Vittorino: dati preliminari sugli studi geologici,* *strutturali, geomorfologici, geofisici e geochimici*. Memorie Società Geologica Italiana, **56**: 297-308.

Deparis J., Jongmans J., Cotton F., Bailler L., Thouvenot F. & Hantz D. (2008) - *Analysis of rock-fall and rock-fall avalanche seismograms in the French Alps.* Bul Seism Soc of America, **98** (2): 1781-1796.

Heng IS. (2009) - *Rotating stellar core-collapse waveform decomposition: a principal component analysis approach.* Class Quantum Grav, **26:** 105005.

Hutchinson J.N. (1988) - *General report: morphological and geotechnical parameters of landslides in relation to geology and hydrogeology.* In: Proceedings of 5th international symposium on landslides, Lausanne, Balkema, Rotterdam: 3-36.

Itaba S. & Ando R. (2011) - *A slow slip event triggered by teleseismic surface waves.* Geophysical Research Letter, **38**: L21306, doi:10.1029/2011GL049593.

Johnston M.J.S. & Mauk F.J. (1972) - *Earth tides and the triggering of eruptions from Mt. Stromboli, Italy.* Nature, **239**: 266-267.

Kasahara J. (2002) - *Tides, earthquakes, and volcanoes.* Science, **297**: 348-349.

Lai X.P., Cai M.F. & Xie M.W. (2006) - *In situ monitoring and analysis of rock mass behavior prior to collapse of the main transport roadway in Linglong Gold Mine, China*. Int J Rock Mech Min Sci, **43**: 640-646.

Lei X., Masuda K., Nishizawa O., Jouniaux L., Liu L., Ma W., Satoh T. & Kusunose K .(2004) - *Detailed analysis of acoustic emission activity during catastrophic fracture of faults in rock.* Journal of Structural Geology, **26**: 247-258.

Lenti L., Martino S., Paciello A., Prestininzi A. & Rivellino S. (2012) - *Microseismicity within a karstified rock mass due to cracks and collapses triggered by earthquakes and gravitational deformations*. Natural Hazards, **64**: 359-379.

Maffei A.,Martino S. & Prestininzi A. (2005) - *From the geological to the numerical model in the analysis of the gravity-induced slope deformations: an example from the Central Apennines (Italy)*. Engineering Geology, **78**: 215-236.

Martino S., Prestininzi A. & Scarascia Mugnozza G. (2004) - *Geological-evolutionary model of a gravity-induced slope deformation in the carbonate central Apennines (Italy)*. Q J Eng Geol and Hydr, **37**(1): 31-47.

McNutt S.R. & Beavan R.J. (1981) - *Volcanic earthquakes at Pavlof volcano correlated with the solid Earth tide.* Nature, **294**: 615-618.

Miller A., Richards J.A., McCann D.M., Browitt C.W.A. & Jackson P.D. (1989) - *Microseismic techniques for monitoring incipient hazardous collapse conditions above abandoned limestone mines.* Q J Eng Geol Lond, **22**: 1-18.

Myiazawa M., Nakanishi I., Sudo Y. & Ohkura T. (2005) - *Dynamic response of frequent tremors at Aso volcano to teleseismic waves from the 1999 Chi-Chi, Taiwan earthquake.* Journal of Volcanology and Geothermal Research, **147**: 173-186.

Paskaleva I., Aronov A.G., Seroglazov R.R. & Aronova T.I. (2006) - *Characteristic features of induced seismic processes in mining regions exemplified by the potassium salt deposits in Belarus and Bulgaria.* Acta Geod Geoph Hung, **41** (3-4): 293-303.

Phillips W.S., Pearson D.C., Edwards C.L. & Stump B.W. (1997) - *Microseismicity induced by a controlled, mine collapse at white pine, Michigan*. Int J Rock Mech Min Sci, **34** (314), paper 246.

Rydelek P.A., Davis D.M. & Koyanagi P.Y. (1988) - *Tidal triggering of earthquakes swarms at Kilauea Volcano, Hawaii.* Journal Geophysics Research, **93** (B5): 4401-4411.

Savage W.Z. & Varnes D.J. (1987) - *Mechanism of gravitational spreading of steep-sided ridges ("sackung").* Bull Int As Eng Geol, **35:** 31-36.

Sottili G., Martino S., Palladino D.M., Paciello A. & Bozzano F. (2007) - *Effects of tidal stresses on volcanic activity at Mount Etna, Italy.* Geophys. Res. Lett., **34** (L01311), doi:10.1029/2006GL028190.

Szwedzicki T. (2003) - *Rock mass behaviour prior to failure*. Int J Rock Mech Min Sci, **40**: 573-584.

Yang X., Stump B.W. & Phillips W.S. (1998) - *Source mechanism of an explosively induced mine collapse.* Bullettin Seismological Society of America, **88** (3): 843-854.

Zischinsky U. (1969) - *Uber Sackungen.* Rock Mech, **1**: 30-52.

