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NANOSEISMIC MONITORING FOR DETECTION OF ROCKFALLS: EXPERIMENTS IN QUARRY AREAS

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EXTENDED ABSTRACT

Le frane per crollo da ammassi rocciosi fratturati sono tra i processi di instabilità gravitativa che più frequentemente interessano opere antropiche quali tagli su versanti naturali o artificiali, pareti di cava, trincee stradali, autostradali o ferroviarie, sia per ciò che attiene le aree di distacco che per quelle di accumulo. Nell'ambito dell'applicazione di sistemi di *early warning* per la gestione del rischio geologico legato a queste tipologie di frana, una sperimentazione della tecnica del monitoraggio nanosismometrico è stata effettuata presso due siti estrattivi non più in attività: le "Pirrere" della Baia di Cala Rossa sull'isola di Favignana (Trapani), in Sicilia, e la cava dismessa di Acuto (Frosinone), in Italia Centrale. Il monitoraggio nanosismometrico è una tecnica di indagine che consente di individuare e localizzare deboli eventi sismici, fino a magnitudo locale (M_L) nell'ordine di -3, attraverso l'impiego di quattro sensori sismometrici disposti secondo una specifica geometria di *array* detta SNS (*Seismic Navigation System*).

Nel presente lavoro, mediante il software NanoseismicSuite sono stati analizzati 73 eventi di crollo indotti artificialmente attraverso la caduta controllata di blocchi di roccia nei due siti estrattivi abbandonati; sono stati lanciati, simulando fenomeni di *rockfalls*, rispettivamente 47 blocchi di roccia nella cava di Acuto e 26 eventi in quattro diverse cave a cielo aperto presenti nel settore occidentale di Cala Rossa. Tali eventi, avendo punto epicentrale noto, hanno permesso di determinare il miglior modello di sottosuolo in termini di valori di velocità delle onde P ed S attraverso un'operazione di *back analysis*. L'analisi è stata, infatti, effettuata variando i valori di velocità e scegliendo quelli relativi all'epicentro teorico ottenuto dall'analisi dell'evento che fosse il più vicino possibile al punto reale di impatto del blocco di roccia. Al fine di valutare la sensibilità della geometria dell'*array* SNS e l'influenza del sito di installazione sulla capacità di individuare e localizzare gli eventi, le sperimentazioni sono state condotte sia variando il raggio di apertura che la zona di installazione degli *array*: presso Acuto le acquisizioni di segnale sono state condotte prima con un *array* SNS con apertura di 20 m e successivamente con un *array* di apertura 10 m, mentre presso Cala Rossa l'*array* è stato installato alternativamente all'aperto in un'area di plateau roccioso ed in una galleria facente parte dell'area di cava abbandonata.

Analizzando i dati si è ottenuta una precisione dell'ubicazione epicentrale compresa tra il 10 ed il 22% della distanza che intercorre tra la sorgente e l'*array* nanosismometrico. Il miglior modello di sottosuolo ottenuto per entrambi i casi di studio è risultato avere una velocità delle onde P pari a 900 m/s ed un rapporto V_P/V_S pari a 1.73, valori in accordo con le condizioni di intenso stato di fratturazione delle rocce carbonatiche affioranti nelle due zone di cava. Per gli eventi di crollo indotti la magnitudo M_L è risultata essere compresa tra -2.8 e -1.3; considerando l'energia sviluppata dall'impatto, legata alla massa del blocco ed all'altezza e alla velocità di caduta, non è stato possibile definire una relazione tra magnitudo ed energia, probabilmente a causa delle differenti caratteristiche del punto di impatto dei diversi blocchi. In generale, si è osservato che la precisione di ubicazione degli eventi, in termini di *azimuth* e distanza dal reale epicentro, è risultata paragonabile sia variando l'apertura dell'*array* che variando il sito di installazione. Per il sito sperimentale di Acuto, il processo di *picking* manuale del tempo di primo arrivo delle onde P è risultato essere più affidabile nel caso di *array* con apertura pari a 10 m. La sperimentazione effettuata a Cala Rossa ha permesso, invece, di osservare una migliore capacità di individuazione degli eventi nelle tracce relative all'*array* posizionato in galleria a causa della minore rumorosità di base del sito di installazione.

Tra le registrazioni sismometriche sono state identificate varie tipologie di segnali, oltre a quelli generati dal lancio dei blocchi, alcune riconducibili ad eventi naturali di crollo altre a deboli terremoti. L'analisi dei segnali riferibili alla prima tipologia di eventi naturali, effettuata tenendo in considerazione i modelli di sottosuolo precedentemente calibrati, ha portato all'identificazione in ambedue i siti di aree aventi maggiore suscettibilità a frane per crollo. In definitiva, si può ritenere che i risultati ottenuti in questo studio siano incoraggianti rispetto all'efficacia della tecnica di monitoraggio nanosismometrico nell'individuazione e nell'ubicazione di fenomeni di crollo in roccia e portano a ritenere questa tecnica potenzialmente applicabile in aree in cui tali eventi possono interferire con infrastrutture antropiche.

ABSTRACT

In the frame of early warning and risk mitigation studies for landslide processes involving rock masses, two quarry areas (Cala Rossa Bay in Sicily and Acuto in Central Italy) were monitored with SNS (Seismic Navigation System) arrays. In this study, 73 rockfalls were simulated by launches of rock blocks. This allowed to perform a back analysis for defining the best seismic velocity model of the subsoil half-space; the records related to each impact caused by the rock block launch were managed by the nanoseismic monitoring approach, varying the velocity model to obtain a theoretical epicentre as close as possible to the actual location of the impact point. In order to evaluate the sensibility of the SNS array, the results obtained by different array apertures and positions were compared in terms of azimuth and distance error with respect to the real epicentres. On the other hand, several natural rockfalls were detected; their analysis allowed to identify areas having higher susceptibility to rockfalls by using the previously calibrated subsoil half-space model. Further studies are required to better define the areas prone to rockfall generation in the considered test sites; nevertheless, the here obtained results show an encouraging perspective about the application of the nanoseismic monitoring with respect to vulnerable infrastructures in rockfall prone areas.

Keywords: *nanoseismic monitoring, landslide risk, induced rockfall, quarry activity*

INTRODUCTION

Anthropic activities are often involved in rock failures from cliff slopes (including planar or wedge sliding, fall or toppling mechanisms), as in case of quarry walls, road or railway trenches.

In Italy, the detection of these landslide processes is requested by the technical regulations to perform constructions or to manage workplaces (such as quarries or mines) or infrastructures (such as roads or railways) under safe conditions. As it regards the safety in workplaces, the risk from possible falling of suspended loads is considered as one of the "specific risk" typologies in the most recent national legislation (Law 81/2008 and Legislative Decree 106/2009) in case of activities to be performed outdoors and close to rock walls looming over the workers, from which rock blocks could detach.

A monitoring technique devoted to detect the existence of fallen blocks on railway tracks is being tested by the use of Artificial intelligence Camera Prototype (AiCP) devices (Fantini *et alii*, 2017a). This technique aims at evaluating, in time compatible with the traffic management on the transit line, the evidence of one or more elements on the railway track that can induce an accident to the trains in transit. In this sense, this monitoring approach operates the risk mitigation based on the reduction of the damage to which the exposed vehicle may be subjected, but it does not mitigate the hazard by reducing the probability of such dangerous effects, i.e. by anticipating them through the detection of precursors.

As it regards security of roads and railways, several recent accidents occurred due to rock blocks over rail tracks caused by rockfalls without any alert to the trains in transit. Approximately 87% of the fatal train accidents were due to derailments of trains; in Italy there were 120 fatal train accidents in the last 15 years and, among these, at least 5 are just attributable to the presence of landslides along the railway as in the case of the derailment at the station of Favazzina of an express train led to Reggio Calabria from Roma Termini on 12 May 2001, the derailment of a regional train along the Vinschgau rail-track bound for Merano on 12 April 2010 or the derailment of the intercity train Milano Centrale-Ventimiglia on 17 January 2014.

Rock slides and falls constitute high-hazard phenomena in relation to their high recurrence; nevertheless, there is a limited possibility of detecting precursors of such landslides. Therefore, the most traditional practice of geomechanical surveying focuses on operations consisting in: i) evaluation of the existence of predisposing factors (such as the geostructural setting) to the detachment; ii) evaluation of the degree of stability of the blocks of rock with a higher predisposition to detachment by calculating safety factors referred to toppling models, planar bock sliding or wedge sliding; iii) consolidation procedures for rock walls in their most unstable portions.

Recent vibro-acoustic monitoring techniques, among which the micro- and nano-seismic recordings, can nowadays allow to detect weak to very weak vibrational signals emitted as a result of neofracturing that anticipate phases of rock failure and following collapse (Bottelin *et alii*, 2013; Tang *et alii*, 2015; Kleinbrod *et alii*, 2017). The advantage of these techniques consists in their high resolution and in the suitability of a single instrumental array (arranged in peculiar configurations) to monitor considerable portions of rock mass (up to some hundred meters). Moreover, the refinement of instrumental sensitivity and of techniques for performing statistical analysis of relationships between seismic noise and vibrations allowed to perform analysis and localisation of microseismic events by nanoseismic monitoring (Joswig, 2008; Sick *et alii*, 2014), that applies analyses quite similar to the ones used by classical seismology for low-energy events (i.e. magnitude down to -3). The same techniques allow, in theory, the recognition and location of rock block collapse events; however, the accuracy of the aforementioned techniques for these purposes has not been tested so far.

For this study, several experiments were carried out about the analysis of artificially induced block falls in two Italian abandoned quarry areas: the Acuto quarry (Frosinone, Central Italy) and the "Pirrere" quarries, on the island of Favignana (Sicily). These experiments were focused on a resolution test for nanoseismic monitoring technique, trying to detect and localise rockfalls (Varnes, 1978) having a known impact point.

TEST SITES

The Acuto test site

The Acuto quarry, located in Central Italy (80 km South from Rome) on a carbonate hill, was exploited until the ’80s to produce inert materials for highway embankments construction. The quarry was abandoned in the following and is used as experimental test site since 2015 by the Research Centre for the Geological Risks (CERI) of “Sapienza” University of Rome, in the framework of a cooperation program signed with the Municipality of Acuto. A multi-sensor monitoring system, devoted to detect precursor signals of rock failures and the long-term rock mass deformations due to natural and anthropic forcing actions, is active since 2016 with final goal of providing an early warning signal. The monitoring system consists of: i) a weather station equipped with thermometer, hygrometer, rain gage and anemometer for wind speed and wind direction; ii) six strain-gages on rock matrix and on microfractures; iii) four joint-gages on open joints; iv) a thermocouple for measuring rock mass temperature; v) an Artificial intelligence Camera Prototype (AiCP) for the detection of rockfall events on a railway track there posed to reproduce a real hazard scenarios (Fantini *et alii*, 2017a).

The quarry wall, constituted of Mesozoic limestone, is intensely jointed; moreover, its bottom is covered by a few meter-extended talus of rock debris with highly heterogeneous sizing (Fig. 1). The rock wall is intensely fractured due to persistent joint sets. Geomechanical scanlines and remote surveys performed by using total station and structure for motion technique (Fantini *et alii*, 2017b) allowed to distinguish 5 joint sets: S0 (93/4; dip direction, dip) corresponding to the limestone strata, S1 (131/82), S2 (91/64), S3 (4/80), and S4 (198/86), which play a fundamental role in controlling the slope instabilities, because of its mutual orientation (Hoek, 1973). The stability analysis of the slope, carried out by taking into account the attitude of the measured joint sets, highlighted rock falling, slide or topples as main mechanism that lead the slope to instability and bounded blocks prone-to-failure with an average volume of 0.1 m^3.

The Cala Rossa test site

Favignana is the main of the Aegadian Islands and is located in the North-West Sicily offshore. Aegadian Islands represent part of the Egadi Trust Belt of the Sicilian-Maghrebian system, originated from the deformation of the Meso-Cenozoic Northern

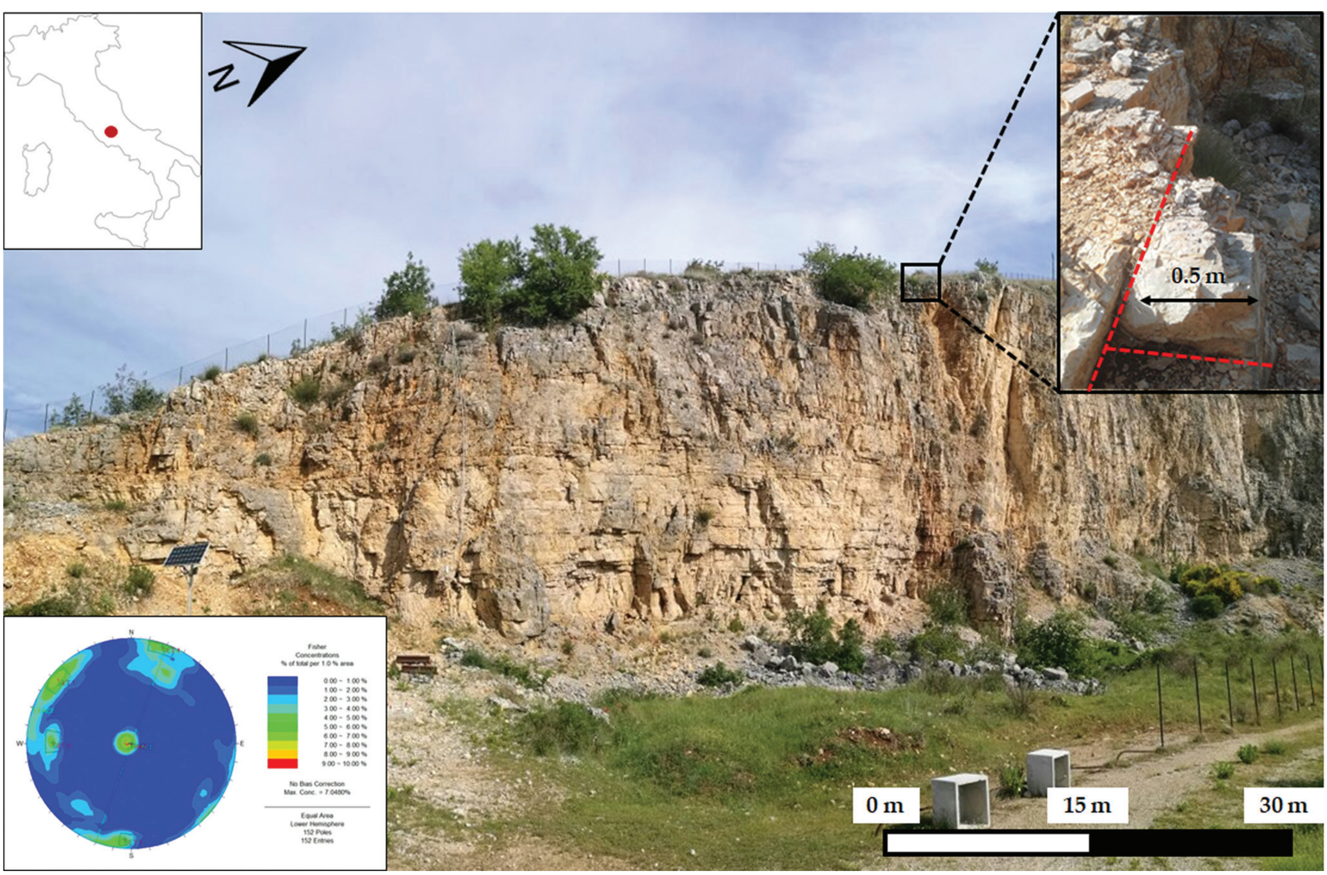

Fig. 1 - Panoramic view of the Acuto quarry rock wall. Main joint sets surveyed through direct geomechanical survey on rock wall are shown through the stereonet; black frame shows the zoom of the pitch of the quarry with detached blocks prone-to-fall (seen from above)

African continental margin (Scandone *et alii*, 1974; Antonioli *et alii*, 2006). Tectonic units, overthrusted in the Middle Miocene and Lower Pliocene, compose the Aegadian Islands as well as the whole Trapani area (Nigro *et alii*, 2000). The Island of Favignana is composed of carbonate rocks of Mesozoic-Lower Tertiary, covered by transgressive Plio-Pleistocene shallow-sea deposits (Abate *et alii*, 1995, 1997; Catalano *et alii*, 1996).

At Cala Rossa Bay, located in the Eastern portion of Favignana, the Plio-Pleistocene shallow-sea deposits outcrop (Abate *et alii*, 1995, 1997; Tondi *et alii*, 2012). Starting from the uppermost formation (Fig. 2), the succession is composed of a porous calcarenite (Lower Pleistocene), having thickness of about 20 m and almost-horizontal strata, over a layer 5-10 m thick of high-plasticity clay (Pliocene). A massive calcarenite (Lower-Middle Miocene) is present under the clay but it does not outcrop at Cala Rossa Bay.

The juxtaposition of stiff rocks (calcarenite) on a ductile substratum (clay) leads to a lateral spreading phenomenon (Goudie, 2004): the lateral spreading of the clayey materials, driven by a visco-plastic rheological behaviour, is responsible for the intense cracking of the overlying stiff rock. Such a mechanism shapes a top-hill plateau bordered by jointed unstable cliffs, favouring the detachment of single rock blocks by typical rock landslide mechanisms, i.e. planar slides, wedge slides, topples and falls (Hoek & Bray, 1981). The resulting landslide is defined of complex type according to Varnes (1978) and Hutchinson (1988).

At Cala Rossa Bay, one of the most important bays of the Favignana eastern sector, a significant lateral spreading process takes place in a rock mass re-shaped by open-air quarries, underground quarries and tunnels, locally named "Pirrere" (Falconi *et alii*, 2015, 2017). Such elements are related to historical mining activities that terminated in the latter half of the last century.

On May 2015, engineering geological surveys and passive seismic investigations were carried out in the western part of Cala Rossa Bay, where the "Pirrere" are located. The engineering geological surveys allowed to reconstruct the geological setting of the cliff slope as well as to measure geomechanical properties of joints (Iannucci *et alii*, 2017). In particular, these surveys were focused on mapping the joints observed on the plateau surface, on the abandoned quarry walls, into the tunnels and on the sea cliff wall; in addition, the abandoned quarry walls were mapped given their tendency to be involved in gravity-induced instability processes.

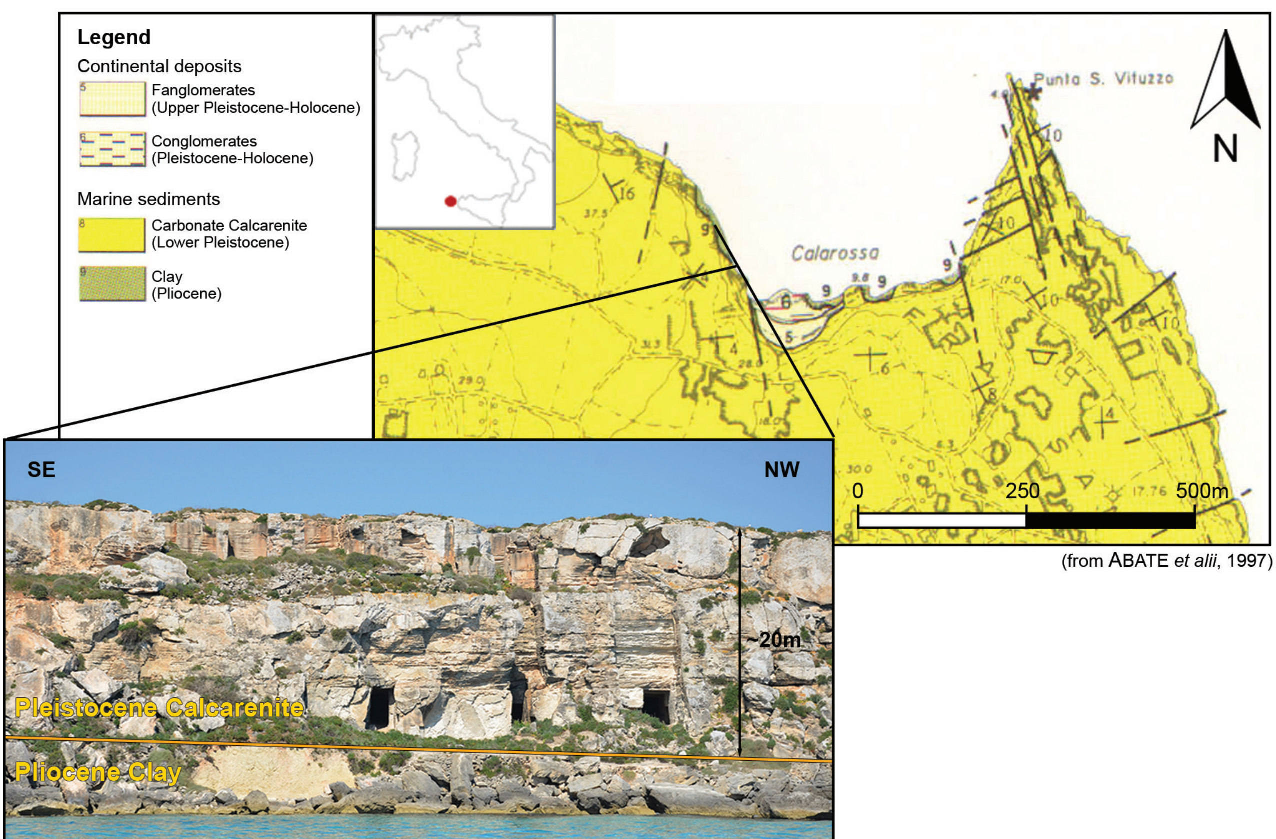

Fig. 2 - Excerpt of Favignana geological map in the Cala Rossa Bay area (from Abate *et alii, 1997) and picture of the sea cliff that shows the overlapping of Lower Pleistocene calcarenite on Pliocene clay*

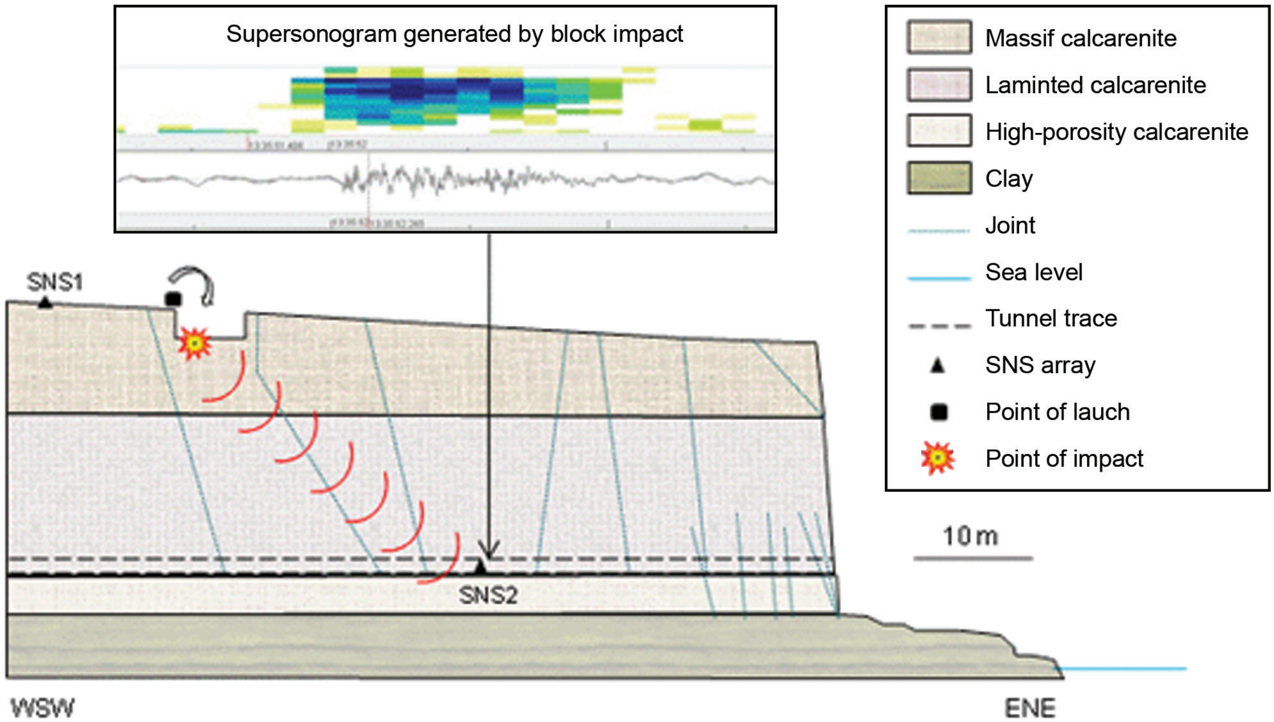

Fig. 3 - Illustration of the experiments: the wave front generated by the launched rock blocks travels within the subsoil and reaches the SNS array located at the surface (SNS1) or in the tunnel (SNS2). Example from the Cala Rossa Bay test site; the cross-section is derived from Iannucci *et alii (2017)*

METHODOLOGY

Experimental approach

In the last fifteen years, the application of specific seismic networks to monitor landslides evidenced the presence of events similar to very-weak earthquakes, related to the slope evolution (Amitrano *et alii*, 2005, 2010; Spillmann *et alii*, 2007; Senfaute *et alii*, 2009; Got *et alii*, 2010; Lévy *et alii*, 2011; Lenti *et alii*, 2012).

Among the proposed techniques to analyse microseismic events, the nanoseismic monitoring (Joswig, 2008) represents an innovative approach to detect and characterise events down to M_L -3. The seismic data are recorded by a specific-geometry array, called Seismic Navigation System (SNS), and managed by the NanoseismicSuite software (www.nanoseismic.net), developed by the Institute for Geophysics of the Stuttgart University. SonoView and HypoLine are the two main tools of this software. SonoView allows to detect events by supersonogram, i.e. a specific spectrogram with noise adaptation, muting and pre-whitening function and a special colour palette that facilitates visual detection (Sick *et alii*, 2014). The events in supersonogram are detectable as anomalies in pixel colour, allowing to evidence them from stationary background noise (Joswig, 1995) and using the "memory image" concept (Joswig, 1990) for a reliable detection even under unfavourable noise conditions. HypoLine (Joswig, 2008) is used to assess the hypocentre location and the local magnitude M_L of the detected events.

Several experiments (Wust-Block & Joswig, 2006; Walter *et alii*, 2012a, 2012b; Fiorucci *et alii*, 2015) demonstrated the reliability of nanoseismic monitoring to detect and locate vibrational events related to rock mass instabilities, e.g. landslides and sinkholes. In particular, Fiorucci *et alii* (2017) evidenced the perspective of nanoseismic monitoring to be integrated in a monitoring system devoted to landslide risk mitigation for threated strategic infrastructures.

In this study, nanoseismic monitoring was applied to locate and characterise controlled rockfalls simulated by launching rock blocks in the two abandoned quarry areas of Acuto and Cala Rossa Bay (Fig. 3). By applying an approach similar to the one tested by Fiorucci *et alii* (2016), the analysis of rock falls with known detachment as well as impact point allows to fix the best-fit subsoil model (i.e. P-wave and S-wave velocities) based on the hypocentre solutions that present the smaller difference with respect to the real hypocentres of the known-origin events (Fig. 4). The obtained subsoil half-space model can be than applied to assess the hypocentre coordinates of events having unknown location, such as natural rockfalls.

Before launching each block, its sizing and weigh as well as the height of the launch point were measured. These measures were used to estimate the initial potential energy of the block and roughly evaluate the theoretical energy generated by its impact on the ground surface; the loss of energy due to previous impacts on the quarry wall or splitting of the block could not be estimated.

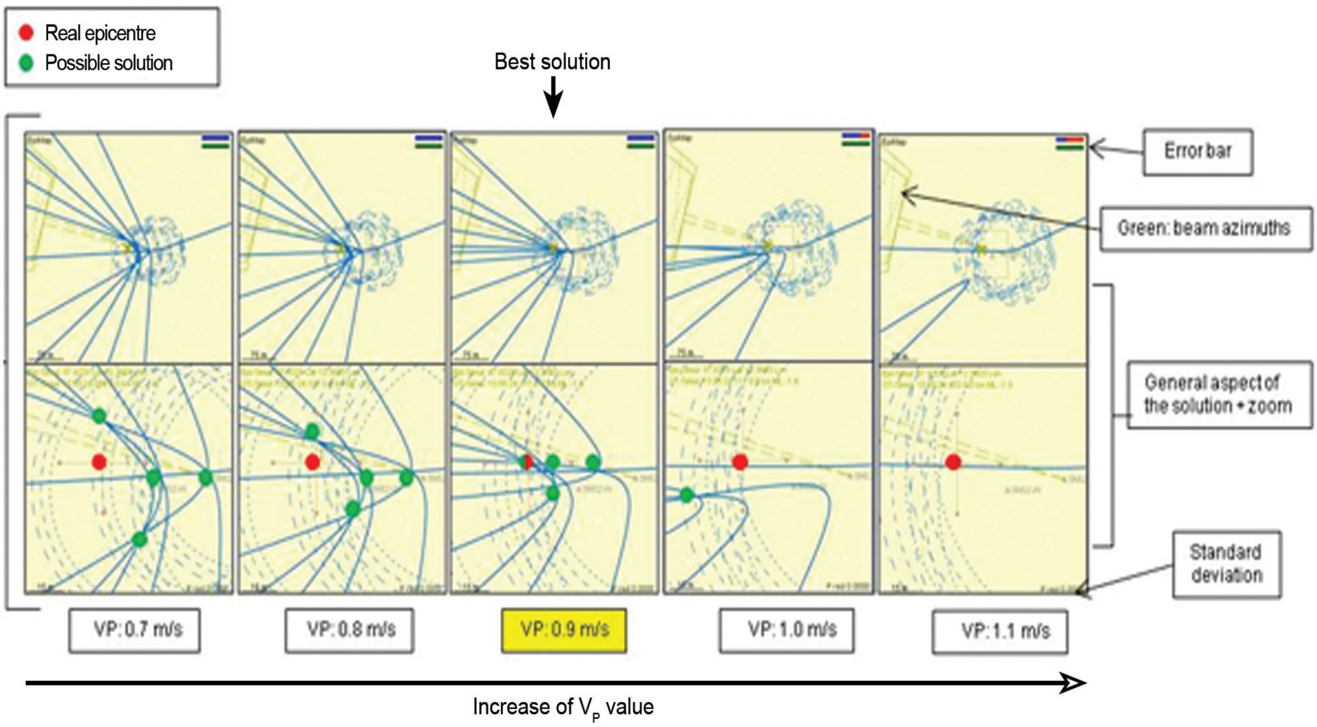

Fig. 4 - Iterative process of hypocentre determination by HypoLine; P-wave velocity value is increased after each computation while depth and V_P/V_S ratio are fixed. Example from the Cala Rossa Bay test site

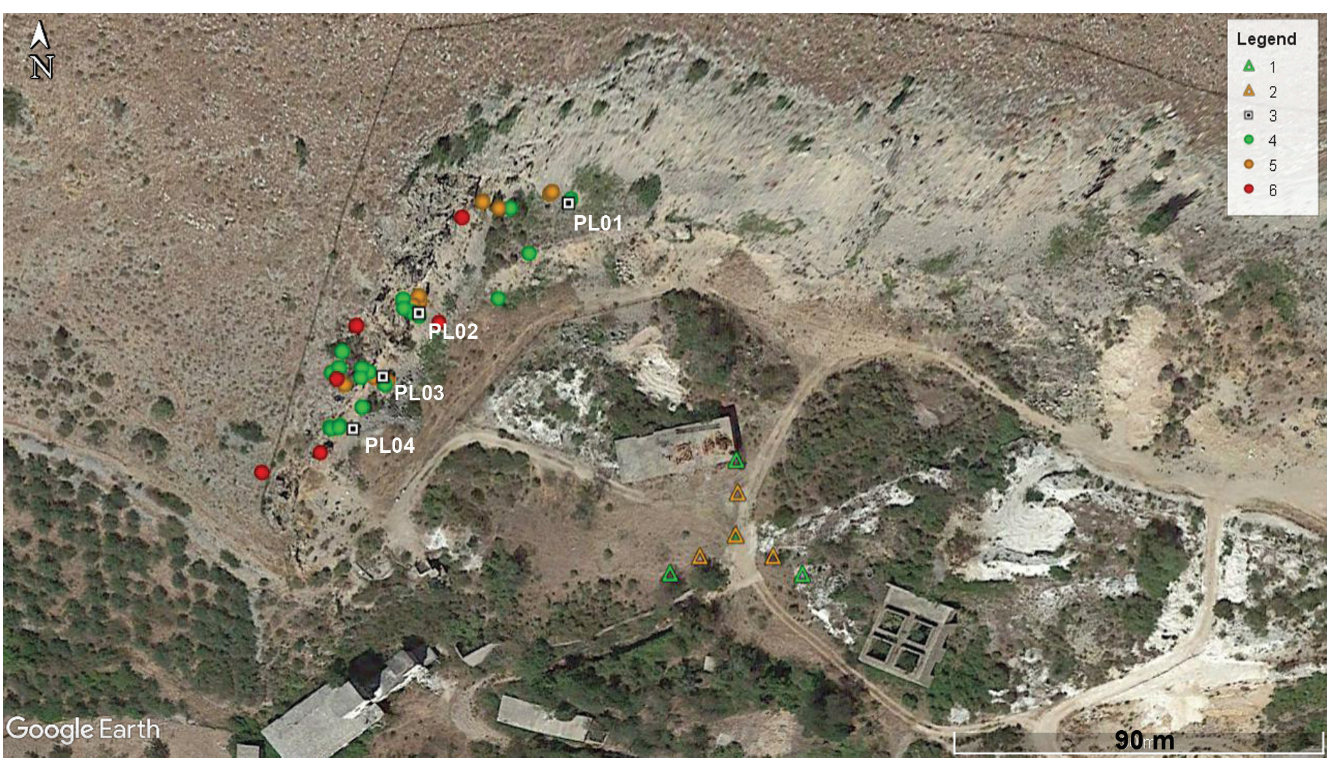

Fig. 5 - Satellite view of the Acuto quarry: 1) array SNS1 (20 m aperture); 2) array SNS2 (10 m aperture); 3) launch point; 4) epicentre of induced rockfall located by SNS1; 5) epicentre of impact located by SNS2; 6) epicentre of natural event

Seismic data acquisition and processing

In both the experimental test sites, the seismic data were collected by arrays with the above-described SNS geometry. Four short-period sensors arranged the SNS arrays: one three-component sensor (named Central Station) at the centre of the array surrounded by three vertical-component sensors (called North, East, West Stations) positioned at 120° to each other, with a distance ranging from 20 to 100 m from the Central Station. The SNS arrays were equipped with four LE-3Dlite MkII seismometers (period 1 s, flat transfer function 1-100 Hz, sensitivity 400 V/m/s) by Lennartz Electronic GmbH coupled with REFTEK 130-01 dataloggers that recorded with a sampling frequency of 500 Hz.

At the Acuto test site, the data by SNS array were recorded during two different campaigns of measurements: the first one on July 2016 and the second one on July 2017. During each campaign, data were recorded for few hours. The data of the first campaign were collected by deploying the SNS array at the base of the quarry, at a distance of about 90 m from the quarry wall, with an aperture of 20 m (SNS1 on Figure 5). During the second campaign, the seismic data were collected in a first stage by installing the SNS array in the position of SNS1 (the same of the previous campaign) and in a second stage by nearing the three outer stations to the Central Station and forming a SNS array with a not-conventional aperture of 10 m (SNS2 on Figure 5). The array SNS1 and SNS2 did not record seismic data simultaneously. The rock blocks were launched from four fixed points (i.e. PL01, PL02, PL03 and PL04 of Figure 5) located at the top of the quarry. At the 4 points the height of the rock wall was significantly different as well as the properties of the ground surface where the impacts occurred, due to the presence or absence of de-bris and to their sizing. During the experimental campaign, 35 impacts were recorded overall by the array SNS1, while 12 impacts were recorded by the SNS2 array (Tab. 1).

At the Cala Rossa test site, the nanoseismic measurements were carried out between 24th May and 1st June 2015 by installing two SNS arrays in two different positions (Fig. 6) for few-hour continuous recording campaigns: the array SNS1 was located on the top of the calcarenite plateau, while the array SNS2 was installed inside an abandoned tunnel just on the top of the clay. Such arrays were alternatively deployed and did not record seismic data simultaneously. The rock blocks were launched from 4 points (i.e. PL01, PL02, PL03 and PL04 of Figure 6) located at the top of the plateau in correspondence to four edges of open-pit quarry rock walls. During the experiment, 26 rock blocks were launched from the four selected locations; more in particular, 12 blocks while the SNS1 array was active and 14 blocks while the SNS2 array was operational (Tab. 2).

RESULTS AND DISCUSSIONS

Results at the Acuto test site

At the Acuto test site, it was possible to detect and locate 35 out of the 47 generated block impacts. The corresponding waveforms are characterised by time duration lower than one second and frequencies ranging from 50 up to 150 Hz (Fig. 7).

Block ID	Launch point	Array	Width (cm)	Length (cm)	Height (cm)	Volume (cm^3)
1	PL03	SNS1	35	30	24	25200
2	PL03	SNS1	38	24	22	20064
3	PL03	SNS1	28	30	19	15960
4	PL03	SNS1	28	36	30	30240
5	PL03	SNS1	40	30	24	28800
6	PL04	SNS1	21	33	14	9702
7	PL04	SNS1	26	13	19	6422
8	PL04	SNS1	33	17	11	6171
9	PL04	SNS1	24	21	17	8568
10	PL04	SNS1	24	17	10	4080
11	PL01	SNS1	20	18	10	3600
12	PL01	SNS1	29	11	25	7975
13	PL01	SNS1	32	21	10	6720
14	PL01	SNS1	18	20	12	4320
15	PL01	SNS1	22	13	15	4290
16	PL02	SNS1	16	25	28	11200
17	PL02	SNS1	28	20	12	6720
18	PL02	SNS1	28	23	17	10948
19	PL02	SNS1	17	18	18	5508
20	PL02	SNS1	22	12	14	3696
21	PL02	SNS1	30	16	14	6720
22	PL02	SNS1	33	10	23	7590
23	PL02	SNS1	80	43	25	86000
A01	PL03	SNS1	30	38	20	22800
A02	PL03	SNS1	45	30	30	40500
A03	PL03	SNS1	52	35	23	41860
A04	PL03	SNS1	40	12	15	7200
A05	PL02	SNS1	58	37	24	51504
A06	PL02	SNS1	40	16	17	10880
A07	PL02	SNS1	27	18	15	7290
A08	PL02	SNS1	33	30	16	15840
A09	PL01	SNS1	25	15	15	5625
A10	PL01	SNS1	33	21	9	6237
A11	PL01	SNS1	30	18	5.5	2970
A12	PL01	SNS1	24	21	10.5	5292
B01	PL03	SNS2	40	34	18	24480
B02	PL03	SNS2	50	30	25	37500
B03	PL03	SNS2	30	40	18	21600
B04	PL03	SNS2	30	25	12	9000
B05	PL02	SNS2	40	53	20	42400
B06	PL02	SNS2	41	14	20	11480
B07	PL02	SNS2	27	19	15	7695
B08	PL02	SNS2	35	17	17	10115
B09	PL01	SNS2	26	21	14	7644
B10	PL01	SNS2	29	23.5	13	8859.5
B11	PL01	SNS2	24.5	17	7	2915.5
B12	PL01	SNS2	15	17	17	4335

Tab. 1 - Properties of the rock blocks launched at Acuto during the experiments with SNS1 and SNS2 arrays

A good correlation resulted between the waveforms detected in the supersonogram and the characteristics of the rock block impacts observed during the field campaign. More in particular, it was possible to distinguish if the rock block impact was on a stiff surface or occurred on a debris cover. In this regard, three typologies of detectability of the events in the supersonogram were distinguished: i) very good detectability (type 1); ii) good detectability (type 2); iii) difficult detectability (type 3). By considering the impact observations collected during the field campaign,

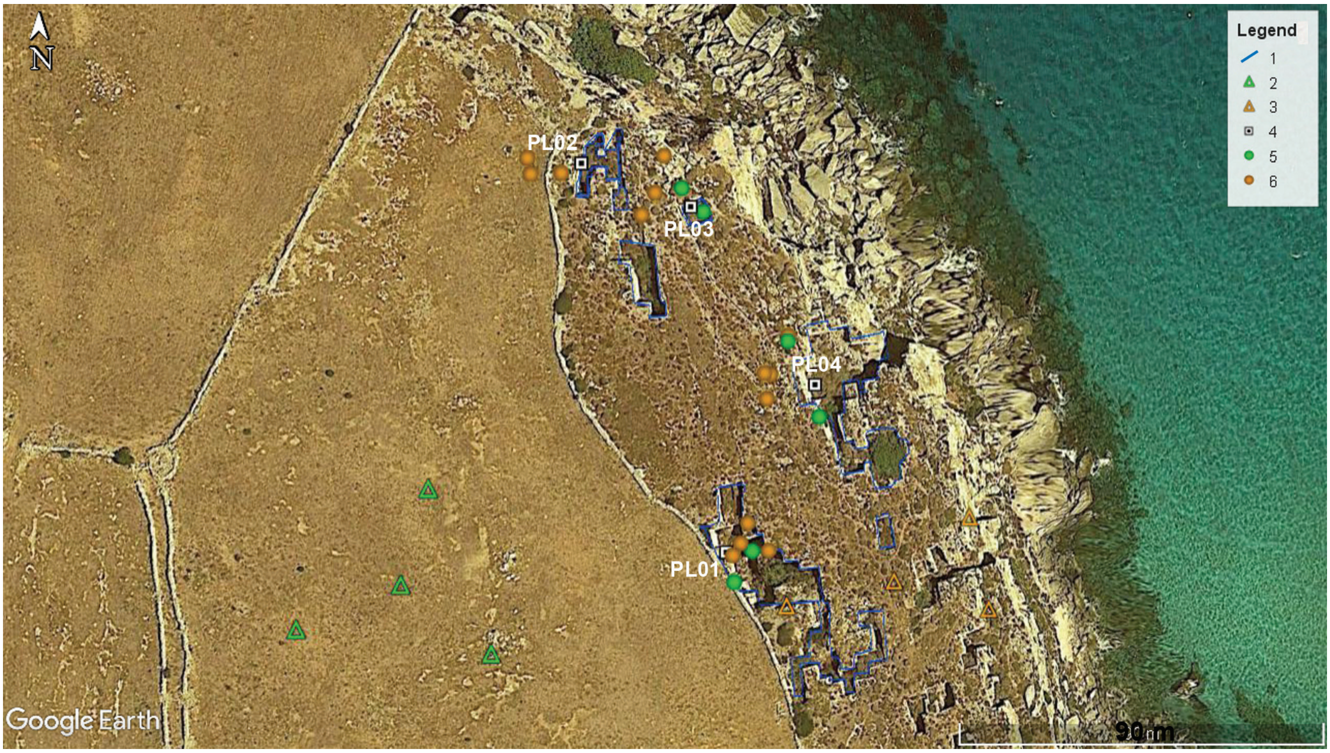

Fig. 6 - Satellite view of the "Pirrere" at Cala Rossa Bay: 1) rock walls of "Pirrere" quarries; 2) array SNS1 (top plateau); 3) array SNS2 (underground); 4) launch point; 5) epicentre of impact located through SNS1; 6) epicentre of impact located through SNS2

Block ID	Launch point	Array	Width (cm)	Length (cm)	Height (cm)	Volume (cm^3)
B01	PL01	SNS2	45	40	17	30600
B02	PL01	SNS1	36	35	20	25200
B03	PL01	SNS1	50	36	8	14400
B04	PL01	SNS2	50	35	10	17500
B05	PL01	SNS1	48	30	7	10080
B06	PL01	SNS2	60	50	18	54000
B07	PL02	SNS2	15	52	23	17940
B08	PL02	SNS2	28	28	17	13328
B09	PL02	SNS2	29	30	14	12180
B10	PL03	SNS1	36	50	18	32400
B11	PL03	SNS1	40	40	18	28800
B12	PL04	SNS1	18	41	30	22140
B13	PL04	SNS2	33	46	25	37950
B14	PL04	SNS1	24	60	21	30240
B15	PL04	SNS2	32	40	10	12800
B16	PL03	SNS2	62	32	14	27776
B17	PL03	SNS2	40	27	17	18360
B18	PL04	SNS2	35	40	10	14000
B19	PL04	SNS2	25	45	10	11250
B20	PL04	SNS1	40	25	15	15000
B21	PL04	SNS1	25	45	12	13500
B22	PL01	SNS1	30	30	12	10800
B23	PL01	SNS2	40	25	5	5000
B24	PL02	SNS1	30	35	10	10500
B25	PL02	SNS1	35	35	5	6125
B26	PL02	SNS2	35	25	7	6125

Tab. 2 - Sizing of the rock blocks launched at Cala Rossa Bay during the experiments carried out on 2015

the three aforementioned qualities of detection have been related to: i) a unique block fallen on a surface with thin debris; ii) a block fallen on a very unequal surface (many debris) or that have caused the falling of other material; iii) a block that splits into two smaller portions, or more, bumping against the quarry wall or that detached a piece of rock from the quarry wall.

Among the recorded events, 12 were not analysed as there were no reliable anomalies in the supersonogram with respect to the background noise for performing the manual picking of the first arrivals of the seismic waves.

By varying the subsoil properties in the tool of the NanoseismicSuite software, the best fit between modelled and recorded locations was obtained with a homogeneous half-space model having a P-wave velocity of 900 m/s and a V_P/V_S ratio of 1.73. The residual with a model of P-waves velocity of 900 m/s is smaller in most of the cases (Fig. 8), taking into account the sum of the residuals on P-waves and S-waves between the picking that fits best the real epicentre and the first user picking. Such a result also justifies the choice of the model, since it gives the best approximation for the impact epicentre.

Azimuth and distance errors between estimate and real epicentre resulted to be of the same order for 10 m and 20 m aperture arrays. However, a difference was identified in the wave picking process; the wave picking of the 12 signals obtained by the 10 m

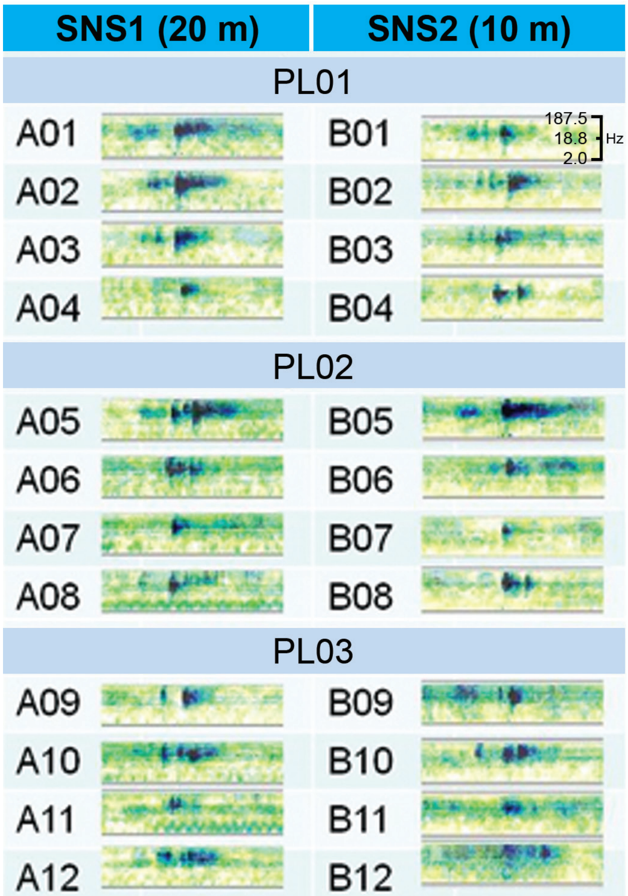

Fig. 7 - Supersonograms of the rock block impacts corresponding to 3 launches at the Acuto quarry

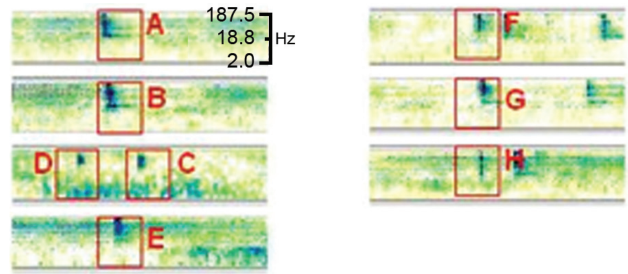

Fig. 9 - Supersonograms rapresenting the natural events at the Acuto quarry

aperture array was easier, even if the signal seemed at first sight less distinguishable.

In addition, eight natural events were analysed by using the previously calibrated subsoil half-space model (Fig. 9). The epicentres result to be distributed at a distance of less of 10 m from the quarry wall and in an area of 1200 m^2 close to the impact of the simulated rockfall experiments (Fig. 5); the magnitude ranges from -3.1 to -2.7. Several additional seismic events were detected on the supersonogram; nevertheless, they were not processed because of difficulties of seismic waves picking, even if they usually presented first arrivals at the West Station and, therefore, their epicentres could be close to those of the eight analysed natural events.

A relation between the energy due to the induced rock block impacts and the related local magnitude M_L was investigated. The kinetic energy related to the impact was calculated for the impact of each launched block recorded at Acuto, by considering the mass of the block and the velocity of falls, derived by using slow motion videos. The energy values were compared with the

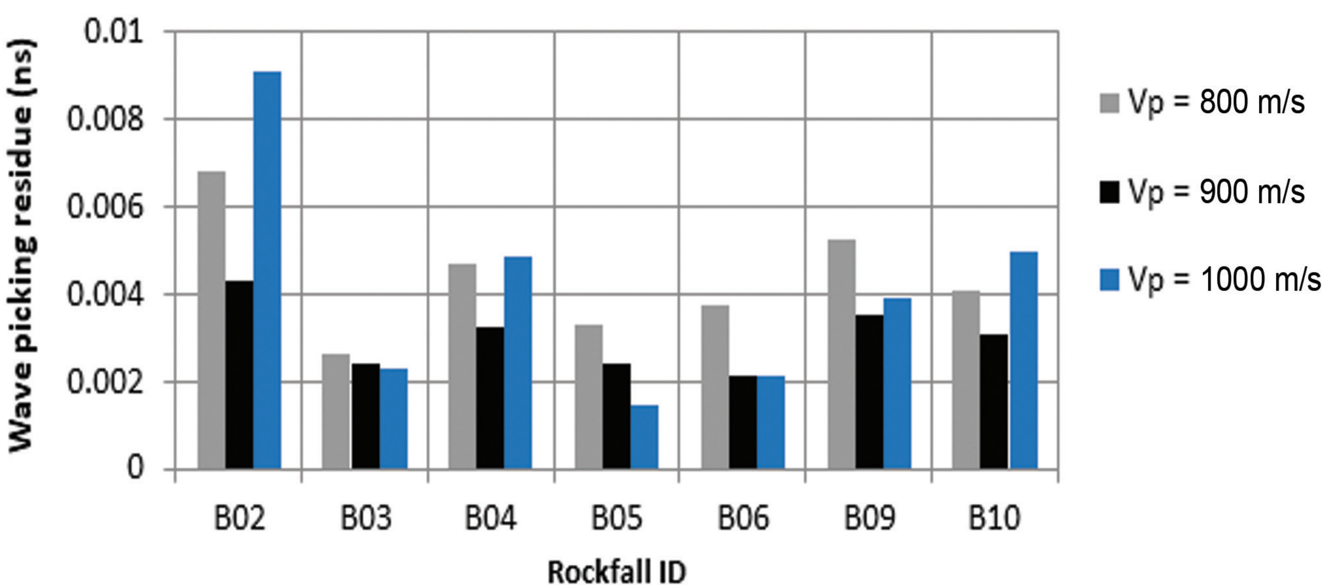

Fig. 8 - Wave picking residual for a selection of impacts corresponding to a impact of a rock block launched at the Acuto quarry

	SNS1 (aperture 20 m)			SNS2 (aperture 10 m)		
Category of energy (J)	Block ID	Energy (J)	M_L	Block ID	Energy (J)	M_L
6000 - 7000	11A	6600	-2.6	11B	6000	-2
7000 - 9000	4A	7100	-2.1	7B	7600	-2.1
	7A	7200	-2.2	12B	8900	-2.4
	-	-	-	4B	8900	-1.4
10000 - 13000	6A	10700	-2.1	8B	10000	-1.7
	9A	11500	-2.1	6B	11300	-1.8
	10A	12800	-2.3	-	-	-
15000 - 25000	8A	15600	-2	10B	18500	-2.1
	1A	24900	-1.9	1B	24100	-1.8
> 40000	2A	39900	-1.5	5B	41800	-1.2

Tab. 3 - Energy (J) classes and related magnitude (M_L) derived for the impact of rock blocks with different size launched at the Acuto quarry

	SNS1 (plateau)			SNS2 (tunnel)		
Category of energy (J)	Block ID	Energy (J)	M_L	Block ID	Energy (J)	M_L
< 3000	B01	2500	-1.7	B20	400	-1.5
	B03	2500	-2.1	B10	1000	-2.4
	B04	2500	-2.1	B15	1000	-2
	-	-	-	B09	1500	-1.7
	-	-	-	B12	1500	-1.8
	-	-	-	B13	1500	-2.2
	-	-	-	B18	1500	-2.1
	-	-	-	B11	2000	-2
	-	-	-	B17	2000	-2
	-	-	-	B19	2000	-1.3
3000 - 6000	B06	3000	-2.2	B08	3000	-2
	B02	4000	-1.5	B07	5000	-1.9
	B05	4000	-2	B14	5000	-1.9
> 6000	-	-	-	B16	9000	-1.7

Tab. 4 - Energy (J) classes and related magnitude (M_L) derived for the impact of rock blocks with different size launched at Cala Rossa Bay

M_L value obtained from HypoLine.

It was not possible to define a relation between the magnitude and the energy value and this seems to be associated to physical limits of the field experiment among which: i) the compared launched blocks were not all of same dimensions; ii) the surface impacts, and the falling path were not the same (for instance a rock block launched and with a first impact on the wall will give off energy on the wall and have less energy at the final impact).

However, five energy classes were defined for the impact of the launched blocks at Acuto by grouping blocks in energy categories (Tab. 3). The tests with a too great energy loss, estimated thanks to field observations, were removed. For the same energy class, the impact magnitude is lower for the SNS array with an aperture of 20 m respect to the one of the SNS array with an aperture of 10 m.

Results at the Cala Rossa Bay test site

At the Cala Rossa Bay test site, 20 rockfalls simulated by rock blocks launch were analysed and located out of 26 totally generated events. All the recorded waveforms were similar to the ones recorded at Acuto in terms of frequency and time duration. The variations observed in terms of shape and intensity of the waveforms can be related to the characteristic of the falling blocks (energy) and to the surface of impact. During the experiment, 6 simulated rockfalls recorded by the SNS1 array (on the plateau) were not suitable to be analysed because of a very intense background noise. On the contrary, all the 14 rock block impacts recorded by the SNS2 array (in the tunnel) were detected and located.

To define a seismic velocity model of the subsoil, the accuracy of the processed epicentres of the 20 rock block impacts ranges from 1 to 18 m, with a mean of 9 m. The accuracy of the epicentre locations accounts for about 7 to 10% of the array-source distance for the plateau array, and 7 to 22% of the array-source distance for data recorded within the tunnel. All the theoretical impacts were correctly positioned in the area of their respective caves (Fig. 6), so demonstrating the good potential of nanoseismic monitoring to locate epicentres related to the falling block impacts.

In addition, nine detected waveforms were associated to as many earthquakes by consulting the earthquake dataset of

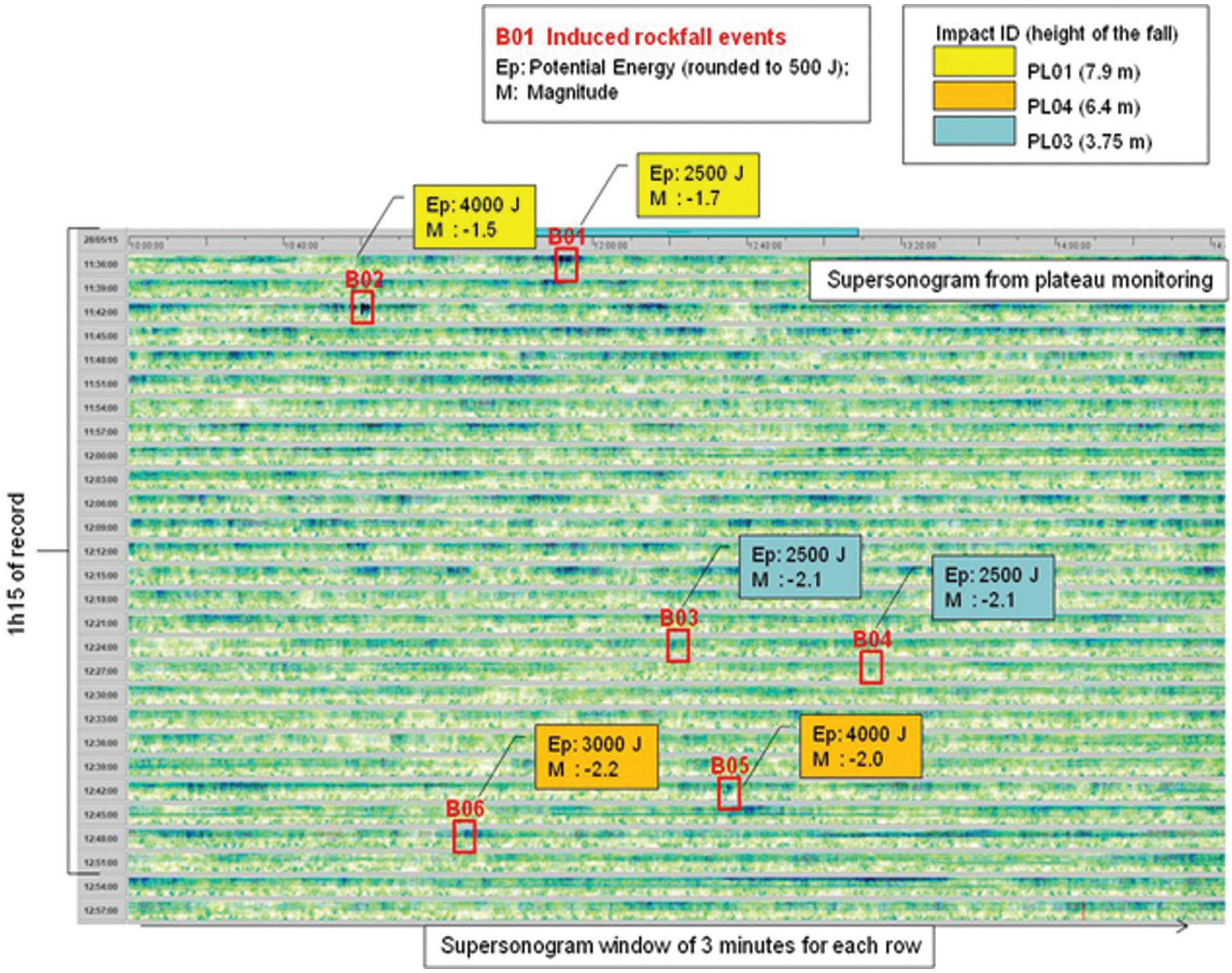

Fig. 10 - Extract of the supersonogram for Cala Rossa Bay from plateau monitoring, with detection of impacts of launched blocks and corresponding values of magnitude and energy

the National Institute of Geophysics and Volcanology of Italy (INGV - http://cnt.rm.ingv.it/); among them four are related to an intense seismic signal, characterised by very clear P-waves arrival. It was possible to attribute hypocentre location and magnitude to these events by using a regional subsoil half-space model with P-wave velocity of 4200 m/s; the obtained results are in very good agreement with the ones attributed by the INGV, confirming the reliability of the used velocity values for the subsoil half-space. Several natural events were also detected, but their epicentres were not defined due to difficulty in picking the first arrivals from the recorded waveforms.

Based on the results obtained at the Cala Rossa Bay, several considerations can be done by taking into account the theoretical energy due to the simulated rockfall events and their detectability in the supersonogram with respect to the background seismic noise intensity (Tab. 4). Since of slow motion videos were not available in this case, the energy of each rock block impact was computed in terms of potential energy only, i.e. by measuring the volume of the block and the falling height. This can be considered as a good approximation because the blocks did not impact on the quarry walls during the fall, at the opposite of what occurred for the Acuto experiments.

The records obtained on the stiff-rock plateau (Fig. 10) generally presented an intense background noise. Therefore, the event detection would have been very difficult or impossible in some cases without the information of the rock block impact time. In case of records with a high background seismic noise, the detection of natural events results to be highly uncertain when the potential energy is lower than 2500 J while in case of low seismic background noise the detection of natural events is highly uncer-

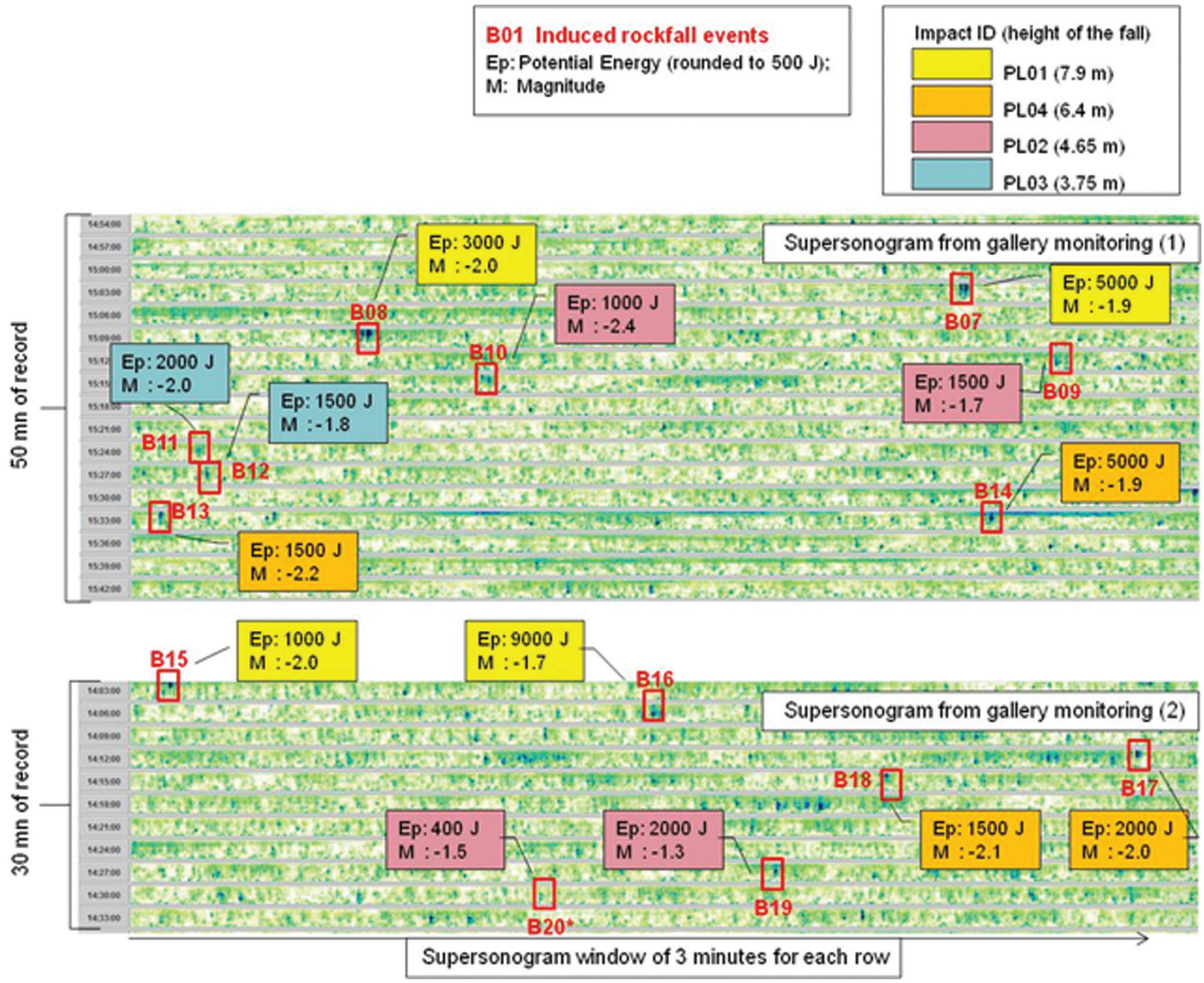

Fig. 11 - Extract of the supersonogram for Cala Rossa Bay from plateau monitoring, with detection of impacts of launched blocks and corresponding values of magnitude and energy

tain if the potential energy is lower than 1000 J.

The records within the underground tunnel (Fig. 11) resulted overall less noisy, however a repetitive presence of anomalies at about 80±40 Hz, occurred every 3-10 s; the source of this noise, characterised by a repetitive scheme, was not identified.

As it resulted from the performed experiments, in case of records with an intense background seismic noise, the detection of events is highly dependent on the impact location: i) from the PL01 rock wall, events with an impact energy value of 2500 J (32 kg rockfall by launched block from 7.9 m) are not detectable; ii) from the PL03 rock wall, events with an impact energy value of 2500 J (67 kg from 3.8 m) are not detectable; iii) from the PL04 rock wall, events with an impact energy value of 4000 J (63 kg from 6.4 m) are not detectable.

CONCLUSIONS

The here presented experiments provided a dataset including simulated and natural rockfalls detected in two abandoned quarries (at Cala Rossa Bay, in Sicily, and at Acuto, in Central Italy) to evaluate the suitability of the nanoseismic monitoring technique for rockfall risk mitigation. The experiments were carried out by arranging SNS arrays and varying their aperture from 10 up to 20 m (at Acuto test site) as well as moving it from an open-air zone to a tunnel (at Cala Rossa Bay).

By rock block launches, 73 impacts were generated on debris cover or stiff rock surfaces allowing to perform a back analysis and to define the best seismic velocity model of the subsoil half-space, deriving a P-wave velocity in the subsoil half-space of 900 m/s. The epicentre of each impact was located with an accuracy varying from 10% up to 22% of the distance between the rock block impact point and the SNS array. The magnitude M_L was estimated in a range from -2.8 to -1.3.

At the Acuto test site, the location accuracy was evaluated taking into account two different arrangements of the SNS array, i.e. with a 20 m and a 10 m aperture respectively. The obtained results demonstrate that the epicentre location error is almost the same for the tested array apertures, even if the wave picking process resulted to be easier in the case of SNS with 10 m of aperture.

The detectability of the simulated rockfalls resulted strongly influenced by the background noise condition of the seismic records. As a matter of fact, at Cala Rossa Bay several induced rock block impacts were not analysed due to the intense background noise measured on the open area (i.e. the stiff rock plateau) while the measures performed in the tunnel resulted more suitable for epicentre location since they were less noisy.

Even if further studies could refine the nanoseismic technique for identifying detachment areas of natural rockfalls. According to the here obtained experimental results the nanoseismic monitoring seems to be a promising approach to be experienced for mitigating the landslide risk related to natural rockfalls.

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