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Monitoring of the vibration induced on the Arno masonry embankment wall by the conservation works after the May 25, 2016 riverbank landslide

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Abstract

Background: The concepts of disaster risk reduction and disaster risk management involve the development, improvement, and application of policies, strategies, and practices to minimize disaster risks throughout society. Nowadays, preserving architectural heritage and ancient monuments from disasters is an important issue in the cultural life of modern societies. The “health” of a building/structure may be evaluate by its deterioration or damage level: monitor the aging and promptly detect relevant damages, play a central role, and structure dynamic characterization and microtremor analysis are considered powerful techniques in this field. A wide bibliography about structures/buildings seismic dynamic characterization is counterpoised to a missing one about their seismic response during conservation/safety works. This paper focus on the seismic response and monitoring of a historical masonry embankment wall during the conservation works carried out after a riverbank landslide that seriously damaged it.

Results: The H/V results of the acquired traces show that main resonance frequency of the masonry embankment wall is between 4 Hz and 15 Hz, in agreement with the frequency range of roughly 10-meters-high, squat and monolithic structure. The whole monitoring period can be divided into three intervals corresponding to three different kind of workings: i) piling work; ii) parapet breakdown, excavation, embankment arrangement and foot wall consolidation; iii) backfill and restoring of the original condition, ordinary construction activities. The maximum peak component particle velocity substantial increase during the second period. All the stations have a higher energy content in the 10-20 Hz frequency range, but the spectra analysis clearly shows that the NS component, perpendicular to the wall, is the most stressed one. Moreover, despite the considerable distance from the August 24 Central Italy earthquake epicentre, the earthquake waveform is clearly recognizable at each station. In fact, the energy is focused around 2 Hz and the signals show directivity neither for the spectrum nor for the H/V.

Conclusion: This work may contribute to characterize the vibrations induced by piling work at close range, and help to define the maximum acceptable vibration pattern for such structures, since literature is missing of such case studies. The maximum peak component particle velocity values clearly showed the work advancement. This paper also shows how the H/V technique is a valuable method to estimate the resonant frequency not only of buildings, but also of a squat and monolithic structure like the Lungarno Torrigiani masonry embankment wall.

Keywords: Cultural heritage, Structural health monitoring, Seismic noise vibration, Passive seismic technique, Landslide, Conservation work, Central Italy earthquake, H/V, Firenze, Masonry embankment wall

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Background

Earthquakes, landslides, floods, and volcanic eruptions are the most relevant processes that potentially can damage or increase the risk of human beings, properties or environment itself (Alcantara-Ayala 2002; Binda et al. 2011; Lotti et al. 2015; Morelli et al. 2014, and Del Soldato et al. 2016). They are usually classified as geohazards (Doornkamp 1989), and also could involve the interaction of human activities (McCall 1992; Lekkas 2000, and Morelli et al. 2014). Separate and distinguish the two mentioned contributions (natural and human) is very difficult, especially when a catastrophic event is greatly influenced by the anthropic intervention (Zulherman et al. 2006). Risks, and damages associated with them, are not only caused by the natural phenomena, but also by the exposed elements vulnerability (Fedeski and Gwilliam 2007). Although risk can be considered the combination of the probability that a threatening event occur, and its possible effects (Pazzi et al. 2016b), it is a complex concept, and as vulnerability, is defined in many ways, depending on the contexts (Cardona 2004; Aven 2010; Pazzi et al. 2016a; Romão et al. 2016). According to Aven (2010) risk could be used to refer a) to situations associated with a small occurring probabilities but that could involve potential large consequences, b) to frequently occurring events with rather small consequences, and c) to occurrences which the possible outcomes and the associated probabilities are equal. Moreover, action and decision are implicit in the definition of risk since it requires to establish the interactions between the subjective risk perception and the scientific requisite for an objective measurement (Pazzi et al. 2016b).

The United Nations Educational, Scientific and Cultural Organization (UNESCO) adopted in 1972 the Convention concerning the Protection of the World Cultural and Natural Heritage, an international treaty which seeks to encourage the identification, protection and preservation of cultural and natural heritage around the world considered to be of outstanding value to humanity. In order to define new approaches to reduce the disasters impact on society, i.e., to focus on Disaster Risk Reduction (DRR), and Disaster Risk Management (DRM), several international initiatives have been supported until today (Romão et al. 2016). Among these, the first has been the Hyogo Framework for Action (HFA, <https://www.unisdr.org/we/coordinate/hfa>) 2005–2015, which set targets and commitments for DRR. Nowadays, the HFA was replaced by the Sendai Framework for Disaster Risk Reduction 2015–2030 (SFDRR, <http://www.unisdr.org/we/coordinate/sendai-framework>), which explicitly recognized the importance of preserving architectural heritage and ancient monuments, and the irreplaceable value for society of historical and cultural heritage. Nevertheless, even though cultural heritage has been recognized as a key resource to build resilient societies (Jigyasu et al. 2013), the world architectural wealth is accumulating damages and heavy losses because of the materials deterioration and the exceptional events, both natural or man-made

(Aguilar et al. 2015). In civil engineering, the “health” of a structure is defined as its deterioration or damage level. Monitor the structures aging and promptly detect relevant damages, i.e., the “Structural Health Monitoring” (SHM) according to Chang et al. (2003) and Ceravolo et al. (2014), play a main role to protect, repair, and consolidate the cultural heritage. Because of preservation needs historical structures cannot be analysed through invasive technique. Within this framework, remote sensing techniques (Tapete et al. 2013) and non-destructive methodologies like vibration-based tests (Aguilar et al. 2015) a) provide information on the structure condition, and on existing damages, and b) allow to identify adequate remedial measures (Castellaro et al. 2008; Ceravolo et al. 2014; Pazzi et al. 2016c).

Even though the use of seismic noise technique in densely populated area is hardly to carry out because of the background noise due to the human activities, the structure dynamic characterization and microtremor analysis are considered powerful techniques in SHM. In fact, these methods are normally employed both to test the conservation status of buildings/structures as their natural frequencies, and to assess damping and modal shapes, that are directly related to the structural rigidity and integrity. The bibliography about buildings/structures seismic risk/vulnerability assessment, as well as their seismic dynamic characterization, is wide (Stewart and Fenves 1998; Ramos et al. 2010; Fiaschi et al. 2012; Barbieri et al. 2013; Casolo et al. 2013; Russo 2013; Asteris et al. 2014; Ceravolo et al. 2014; Aguilar et al. 2015; Lacanna et al. 2016 and references within, and Pazzi et al. 2016a, b). On the other hand, papers about the seismic response of structures/buildings during conservation/safety works are missing, even though the seismic vibration monitoring (SVM) is a technique widely used during these kind of works.

This paper is focused on the seismic response and monitoring of the Lungarno Torrigiani (Florence, Italy) masonry embankment wall, during its conservation works after the May 25, 2016 riverbank landslides that seriously damaged it. After a brief description of the study area, and of the applied methodology, the result of the microtremor survey are given. Moreover, the effects of the August 24, 2016 Central Italy earthquake are shown. Static or dynamic analysis of the structure is beyond the scope of this study.

Study area

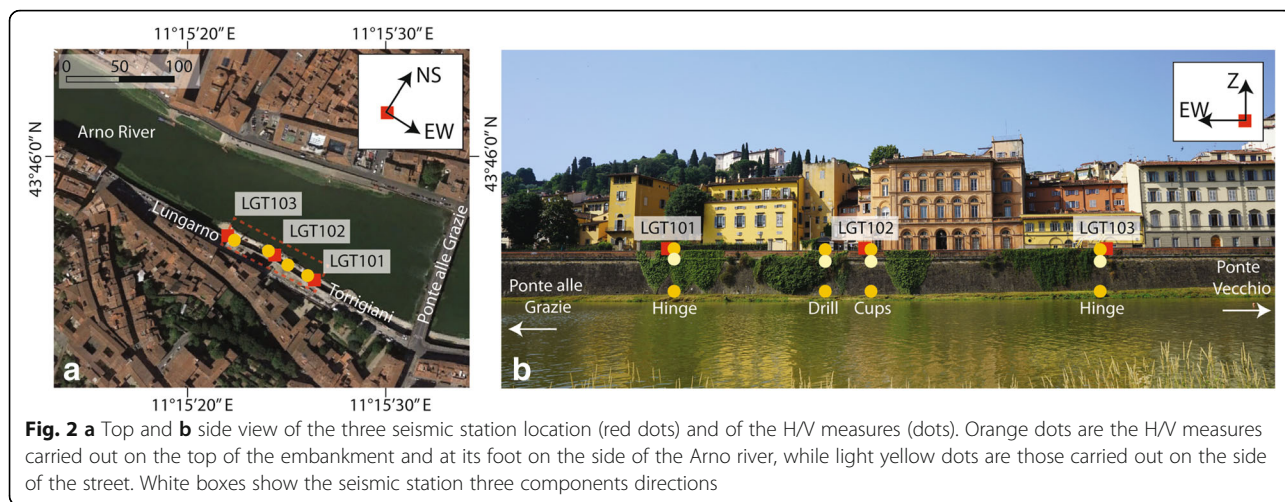
Since 1982 the inner centre of Florence is enumerated in the UNESCO World Heritage List (<http://whc.unesco.org/en/list/174>). The current geomorphological feature of the Florence floodplain is the result of a fluvial-lacustrine basin evolution, dated back to the Plio-Pleistocene epoch as a consequence of the northern Apennines orogenesis extensional phase (Bartolini and Pranzini 1981). The bedrock mainly comprised the Ligurian units, and the paleo-Arno and other minor water-courses alluvial deposits (endorheic drainage system),

according to Boccaletti et al. (2001), reach a maximum thickness of 160 m (90 m in the centre of the city; in the study area: roughly from 9, Ponte Vecchio side, to 30 m, Ponte alle Grazie side). In the past, the Arno river reach that crosses the city of Florence has been subject to numerous riverbed rectifications and other hydraulic works, in order to contrast lateral movements, and to reduce flood risk and reclaim swamps. The first interventions in the urban area of Firenze date back to Roman times, and during the 12th century the whole river

stretch was radically transferred to the current position (Morelli et al. 2012, 2014).

On May 25, 2016 a riverbank landslide occurred at about 6.00 a.m. because of the loss of potable water from the pipe. It was located between Ponte alle Grazie and the Ponte Vecchio on the left river bank of the Florence urban stretch of the Arno river. It involved a portion roughly 100 m long of the Lungarno Torrigiani masonry embankment wall (Fig. 1a, b). The street next to the embankment





wall collapsed (Fig. 1c), and the earth fill material was fully retained by the embankment wall that was seriously deformed towards the Arno river, fracturing itself in three main areas (Fig. 1b, d), but did not collapse. These three main fractured zones are a cusp (Fig. 1b, d, e), roughly in the middle of the damaged wall (Fig. 1b), where is also concentrated the maximum landslide pressure, and two hinges, one on the side of Ponte alle Grazie, and the other one on the side of Ponte Vecchio (Fig. 1b, d). The analysis of the landslide mechanism, of the involved volumes, and of the installed monitoring system will not be discussed in this paper.

The masonry embankment was built between 1865 and 1871 during the “Firenze Capitale” works coordinated by architect Giuseppe Poggi. According to the original Poggi’s project a) the masonry embankment is founded on piles of wood, and b) below the street level runs a 5 m diameter tunnel aimed to drainage the water also coming from the historically unstable hill of San Miniato (Fig. 1f). Above the tunnel is located a sewer pipeline (Fig. 1f). The painting “Ponte alle Grazie and Lungarno Torrigiani” by Fabio Borbottoni (1820–1902) shows that the whole embankment was further back from its current headquarters

(Fig. 1g). The pipe that probably generated the loss was installed in the late 50s – early 60s on the back of the embankment wall (Fig. 1h). Structural damages of the left river bank masonry embankment wall are reported by historical chronical. In 1965 the Lungarno Soderini embankment wall, between Ponte alla Carraia and Ponte Vespucci, collapsed because of a landslide caused by the rupture of the 700 mm water pipes. 5,000 cubic meters of earth were involved, several people were injured, and one died. In 1990 a big crack with a length of 150 m was opened in the same embankment.

Methods

Ancient buildings have higher inherent damping than modern ones, thus they are less susceptible to ground excitations. Moreover, the diversity of materials, the inherent structural strength, the dynamic characteristic, and the construction methods could entail different resonance frequencies or no resonance at all for this type of structures (Asteris et al. 2014 and Asteris and Plevris 2015). All these aspects lead to lower vulnerability of ancient structures to human activities or traffic-

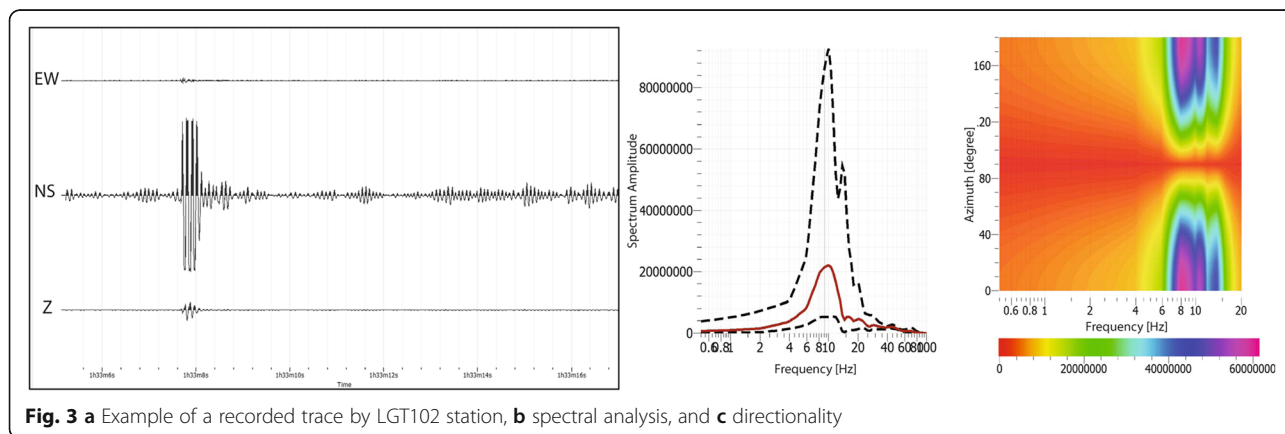


Table 1 Maximum pcpv values recorded during the rotation and roto-percussion piling works

	pcpv (mm/s)					
	NS		EW		Z	
	Rotation	Roto-percussion	Rotation	Roto-percussion	Rotation	Roto-percussion
Drill	1.35	-1.12	0.50	1.25	-0.28	-0.52
Cusp	0.97	3.97	0.29	2.52	-0.11	-1.41
Hinge (Ponte Vecchio side)	1.03	-1.32	-0.58	0.67	0.55	0.33
Hinge (Ponte alle Grazie side)	0.27	-2.76	0.09	-0.52	0.02	0.32

induced ground vibrations. On the other hand, worksite activities, such as piling work that generally operate using higher energy content, stress frequencies that could damage historical structures/buildings.

According to the national and international regulations the assessment of vibrations must be performed in relation to their effect on humans and structures. The UNI9916:2004 (Criteria for the measurement of vibrations and the assessment of their effects on buildings) specifies which parameters have to be measured and the methods of measurement, the characteristics of the employed instrumentation, and data processing, in order to evaluate the vibration phenomena and to allow the assessment of the vibration effects on buildings. It also classifies structure/building damages according to the following terminology: architectural/threshold damages (also called cosmetic damages in the Appendix D.3 according to the regulation BS5228-4:1992: Noise control on construction and open sites - Code of practice for noise and vibration control applicable to piling operations) and major damages. The first ones are superficial or functional alterations that do not compromise the structural stability or the occupants' safety, while the last are structural damages that compromise the stability.

Nevertheless, this regulation does not provide any vibration well-defined limits, even though in Appendix D it lists the standard values suggested by the BS7385:1990 (Evaluation and measurement for vibration in buildings.

Guide for measurement of vibrations and evaluation of their effects on buildings), and by the DIN4150-3:1999 (Erschütterungen im Bauwesen: Einwirkungen auf bauliche Anlagen - Vibrations in buildings: effects on manufactures). This last one is the on site measures standard reference allowing to obtain direct and rapid information on the occurrence of possible structure/building damages. It also classifies the buildings as follows: i) industrial or structurally similar buildings, ii) residential or structurally similar buildings, and iii) buildings worthy of being protected, i.e., cultural heritage. Moreover, according to both the BS7385:1990 and the DIN4150-3:1999, and consequently the UNI9916:2004, the peak particle velocity (ppv) is defined as the maximum value of the module of the velocity vector measured at a given point, while the peak component particle velocity (pcpv) is defined as the maximum value of one of velocity vector three components, measured at the same time at a given point. Finally, these regulations specify that the spectral analysis allows to identify the frequencies and amplitudes of the vibration harmonic components, and compare them with the building/structure resonance frequencies. In general, the vibration harmonic components analysis can be limited up to 250 Hz, or up to 100 Hz calculating the velocity.

The UNI9916:2004 Appendix D.2.1.1 and D.2.1.2 define, according to the DIN4150-3:1999, the short-term and long-term vibrations pcpv standard limits, respectively. This value for the cultural heritage buildings/structures

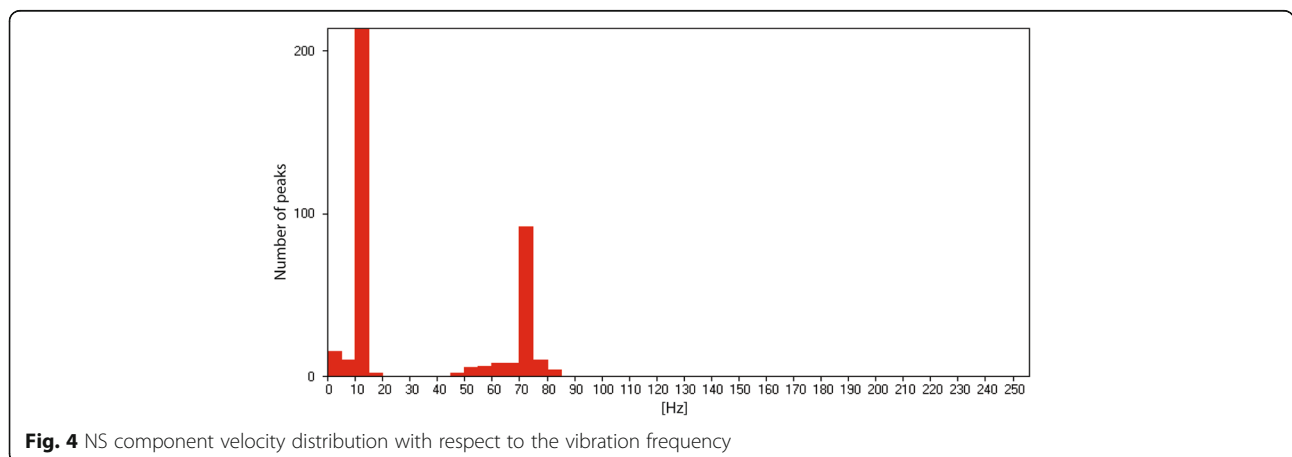
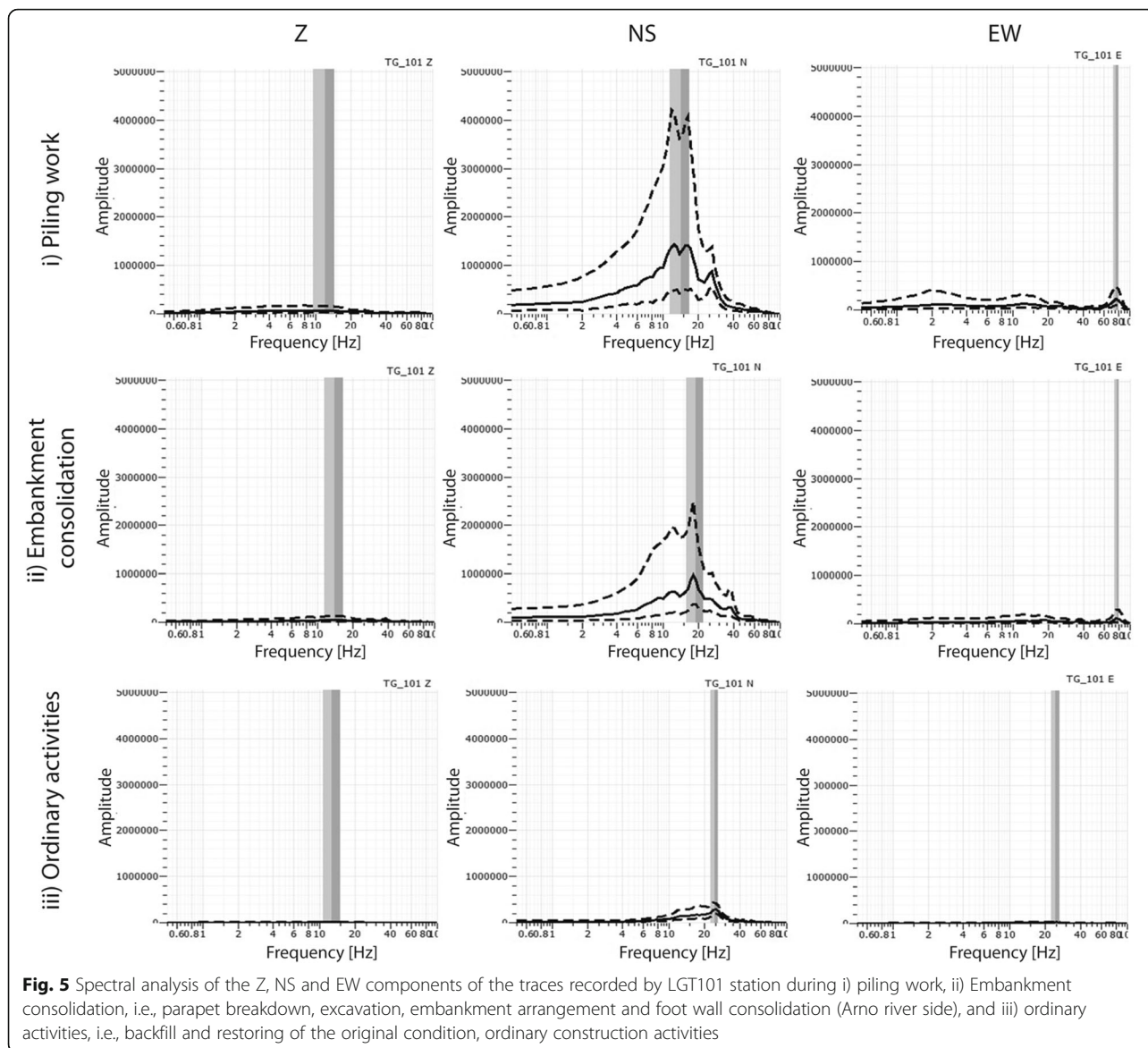


Fig. 4 NS component velocity distribution with respect to the vibration frequency



(class iii) is 2.5 mm/s at any frequency. On the other hand, the UNI9916:2004 Appendix D.4, according to the SN640312:1992 (*Effet des ébranlements sur les constructions - Impact of vibrations on the buildings*), define three ranges for the cultural heritage ppv standard limits, depending on the vibration frequency: 1.5-3 mm/s (vibration frequency: 8–30 Hz), 2–4 mm/s (vibration frequency: 30–60 Hz), and 3–6 mm/s (vibration frequency: 60–150 Hz).

The Lungarno Torrigiani masonry embankment wall, according to the DIN4150-3:1999, is in class iii (buildings/structures worthy of being protected). Therefore, its SVM was drawn up a) to define the resonance frequencies of the wall after the damages caused by the landslide, b) to quantify the vibrations to which the masonry embankment wall was subject during the conservation/consolidation activities (rotation and roto-percussion piling work to install D600

piles and D300 μ piles, both vertical or inclined), c) to verify the possibility of double resonance phenomena caused by workings, and d) to check compatibility with the relevant standards, and any critical conditions.

To set the SVM sampling frequency the fundamental frequency of the masonry embankment wall was evaluated by means of the horizontal to vertical spectral ratio (H/V or HVSR) technique (Nakamura 1989; Lermo and Chavez-Garcia 1993; Fäh et al. 2001, and Carniel et al. 2006), carried out by means of the commercial software Grilla®. The H/V method, in fact, has proven to be one of the most appropriate to estimate the fundamental/resonance frequency of soft deposits (Lermo and Chavez-Garcia 1994; Larose et al. 2015, and Pazzi et al. 2016d), and also to study the interaction between soil and structures (Herak 2008 and Pazzi et al. 2016a, b).

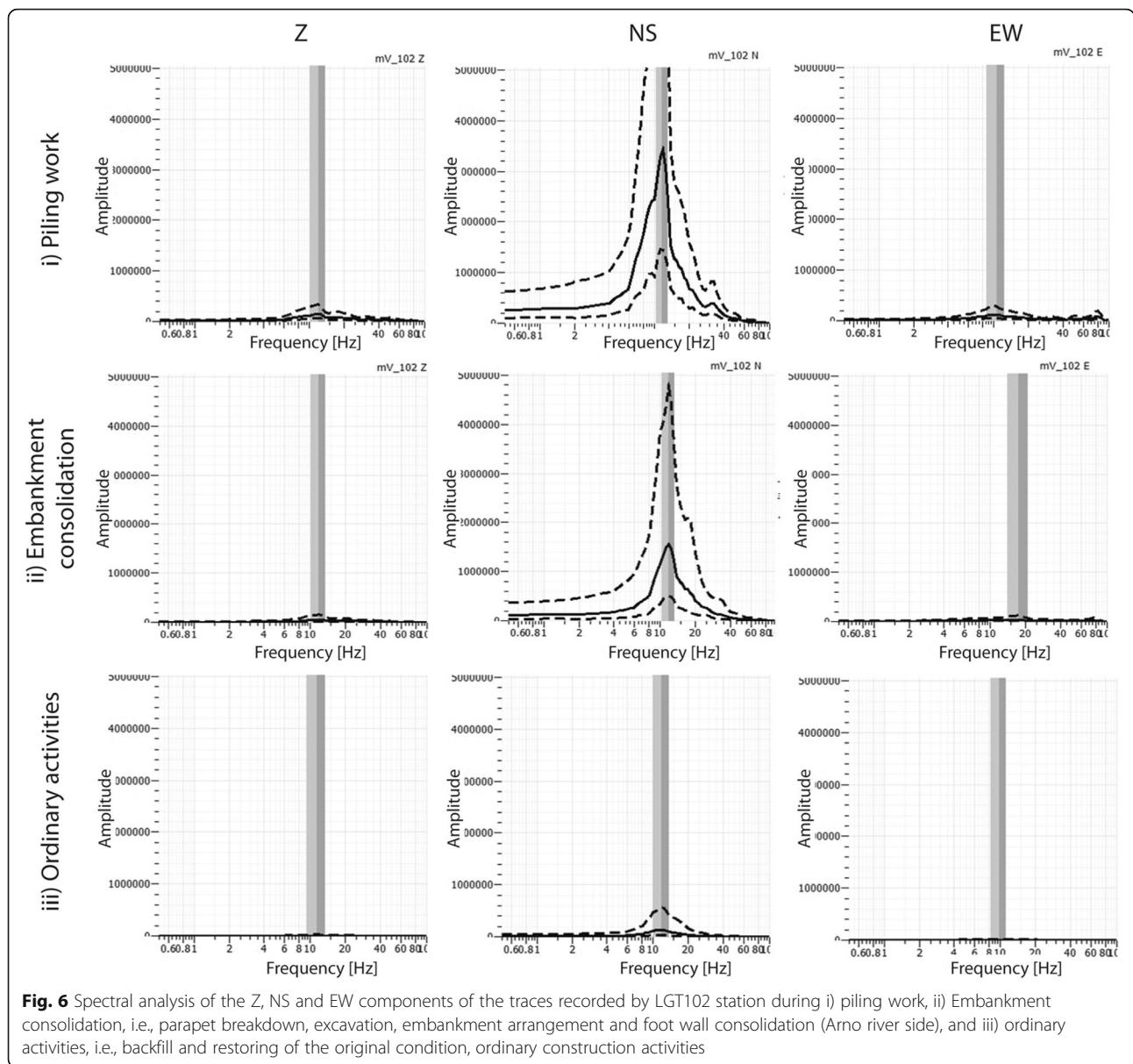
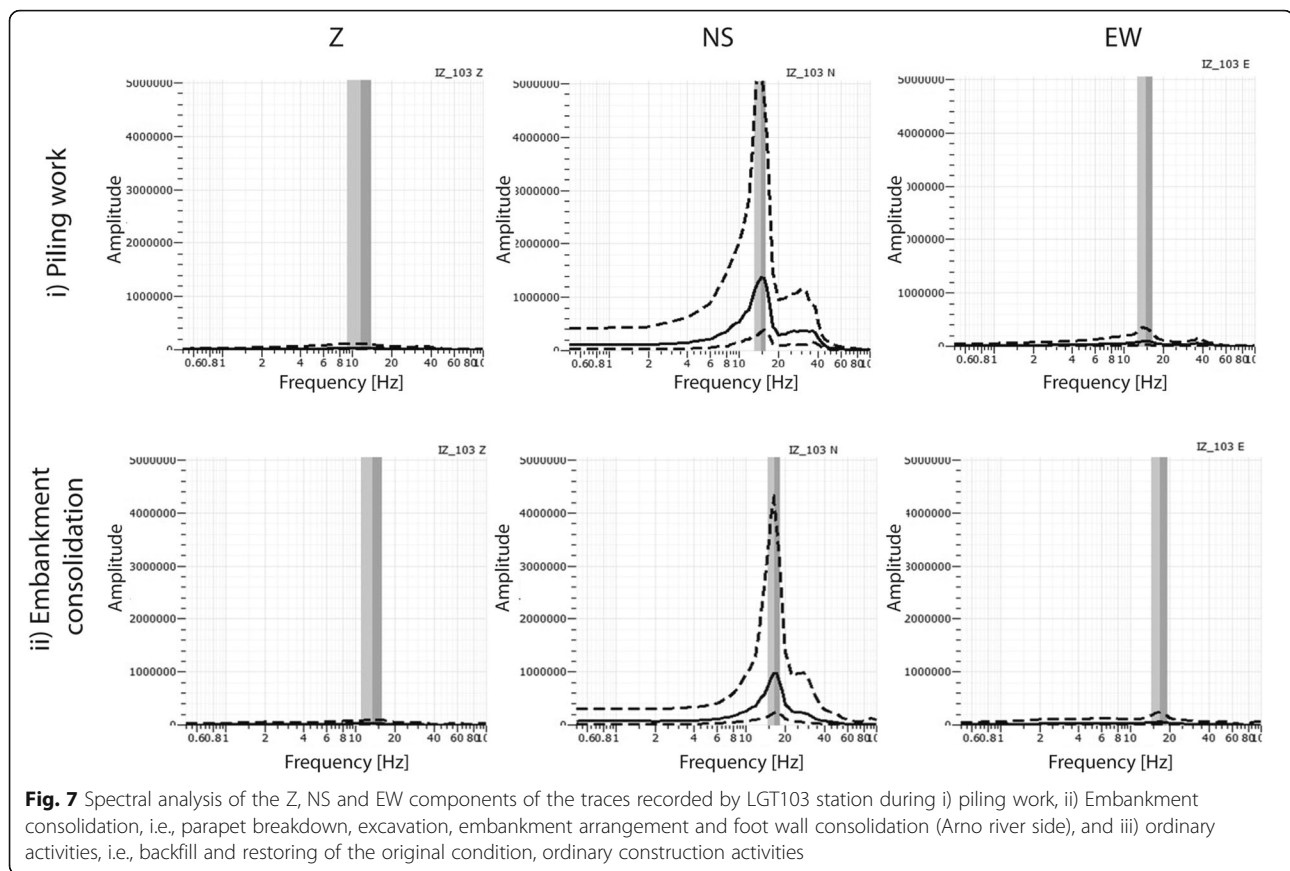


Fig. 6 Spectral analysis of the Z, NS and EW components of the traces recorded by LGT102 station during i) piling work, ii) Embankment consolidation, i.e., parapet breakdown, excavation, embankment arrangement and foot wall consolidation (Arno river side), and iii) ordinary activities, i.e., backfill and restoring of the original condition, ordinary construction activities

Del Gaudio et al. (2014) presented an overview of this technique. We assumed that the masonry embankment wall was a structure equivalent to a building of the same height. Therefore, the measures were carried out simultaneously (Pazzi et al. 2016a, b) on the top (orange dots in Fig. 2) of the masonry embankment wall (as it was the building’s roof) and at its foot (as it was the ground floor or the free field measure), both on the side of the river (orange dots in Fig. 2) and of the street (as it was a building floor, light yellow dots in Fig. 2b). These 5 min long seismic noise records at 512 Hz were carried out on August 13th, by means of two Tromino®, the all-in-one compact 3-directional 24-bit digital tromometer developed by MoHo s.r.l..

The SVM was carried out from August 14 to October 10th, 2016 by means of three high gain triaxle velocimeters SS45 (own frequency 4.5 Hz, each one coupled with a SL06 24-bit digitiser, provided by Sara Electronic Instruments (red square in Fig. 2). The seismic stations were located onto the masonry embankment wall, in the three structurally more fragile and fractured areas: LGT101 near the hinge on the side of Ponte alle Grazie, LGT102 near the cusp, and LGT103 near the hinge on the side of Ponte Vecchio. The NS component of each station was perpendicular to the wall, the EW parallel, and the Z was the up-and-down component. As shown in Fig. 2 (white boxes), positive values of the NS component were associated with embankment wall



movements towards the Arno river (North North-East), while negative ones with movements towards the inside (South South-West), i.e., the street. Consequently, EW components positive values were associated with movements towards Ponte alle Grazie (East South-East), while negative values towards “Ponte Vecchio” (North North-West). To assess the true comparability of the Tromino® and Sara Electronic sensors responses, a “huddle test” ran for all the instruments prior to measurements.

The sampling frequency was 200 Hz since the detected vibrating frequencies range of interest was 1–100 Hz (Aguilar et al. 2015). The Geopsy® software was employed a) to analyse, process, and carry out the spectral analysis of the whole dataset, since it applies the SESAME project (2004) standards and guidelines for processing ambient vibration data, b) to calculate the pcgv values four time a day (i.e., every 6 h), and c) to evaluate the directionality of each spectral peak (Del Gaudio et al. 2008) (Fig. 3).

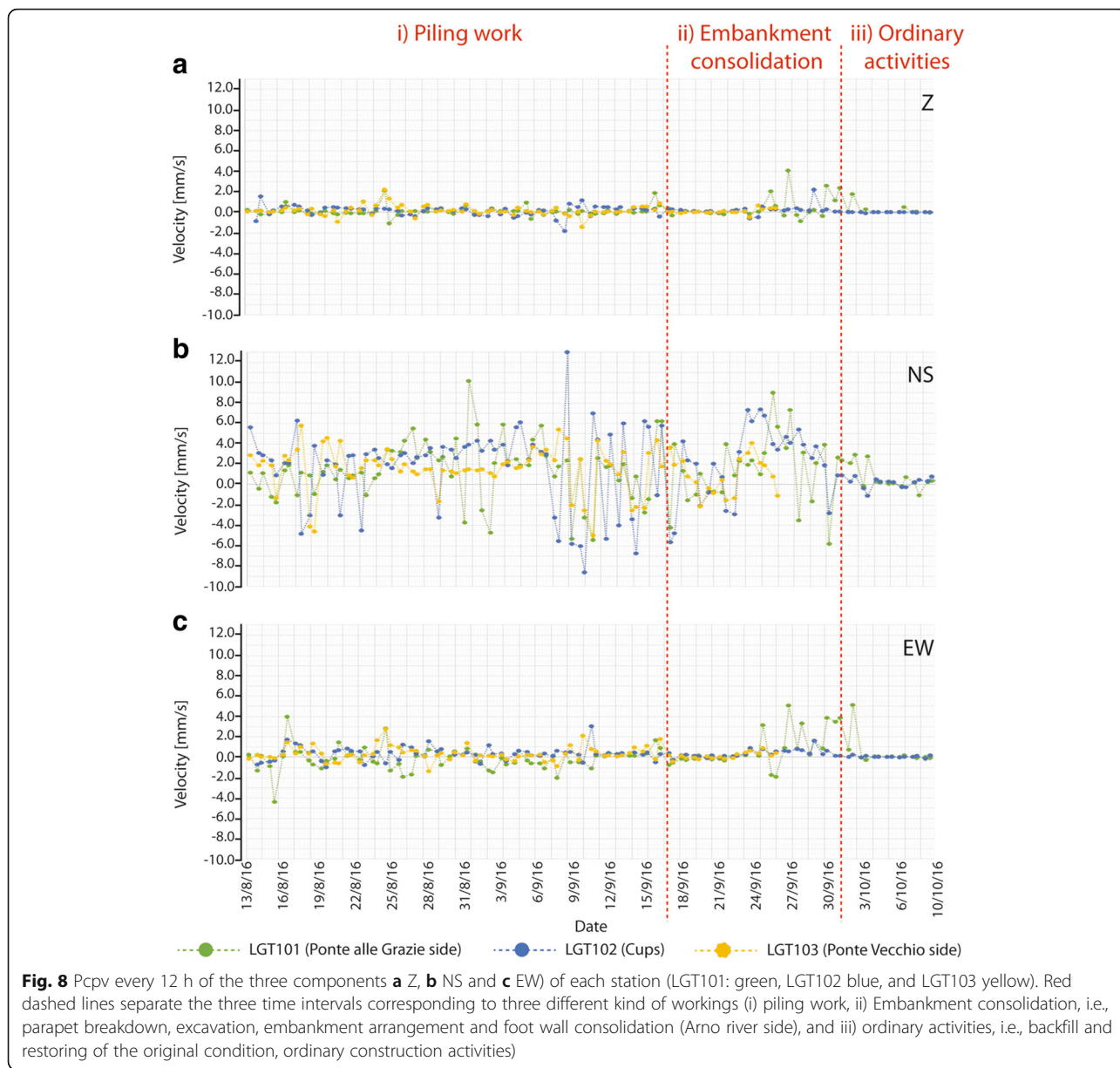
Results and discussion

The H/V results of the traces acquired to evaluate the resonance frequency of the masonry embankment wall

show that its main resonance frequency is between 4 Hz and 15 Hz, in agreement with the frequency range of roughly 10-m-high, squat and monolithic structure (according to the well know Pratt’s equation, and Diaferio et al. 2015a, b). The maximum pcgv values recorded during the rotation and roto-percussion piling work are listed in Table 1. As expected, there is a substantial increase of the velocity values during the roto-percussion drillings.

Figure 4 shows the LGT102 NS component (the most stressed) velocity distribution with respect to the vibration frequency. The most stressed frequencies (more than 300 time series) that exceed a pre-determined threshold set equal to 2.5 mm/s, according to the pcgv standard limits, are located in the range of 10–15 Hz (over 200 times) and 70–75 Hz (about 90 times). The velocity peaks > 3.50 mm/s have a frequency of roughly 5 Hz (Fig. 4).

Taking into account the natural resonance frequency of the masonry embankment wall, double resonance phenomena could not be excluded. Since no case studies like this are available in literature, this paper may contribute to characterize the vibrations induced by piling work at close range. Moreover, it may help to



define the maximum acceptable vibration pattern for such structures. Nevertheless, the choice of a predetermined safety threshold, in terms of vibrational solicitations, both continuous and impulsive, is a difficult task in this case study because of the lack of a complete structural model of the masonry embankment wall. Only fragmentary information about the wall foundation and its internal structure are available.

For the aforementioned reason, we will simply present the results of the continuous monitoring. The whole monitoring period can be divided into three intervals corresponding to three different kind of

workings: i) 13.08.2016 – 16.09.2016 (35 days): piling work; ii) 16.09.2016 – 01.10.2016 (16 days): parapet breakdown, excavation, embankment arrangement and foot wall consolidation (Arno river side); iii) 01.10.2016 – 10.10.2016 (10 days): backfill and restoring of the original condition, ordinary construction activities. The spectra analysis (Figs. 5–7) clearly show that the NS component, perpendicular to the wall, is the most stressed one (consistently with preliminary tests observations) until the end of the piling work (16.09.2016, 1:00 p.m.). Detailed observation of the spectrum reveals that all the stations have a higher

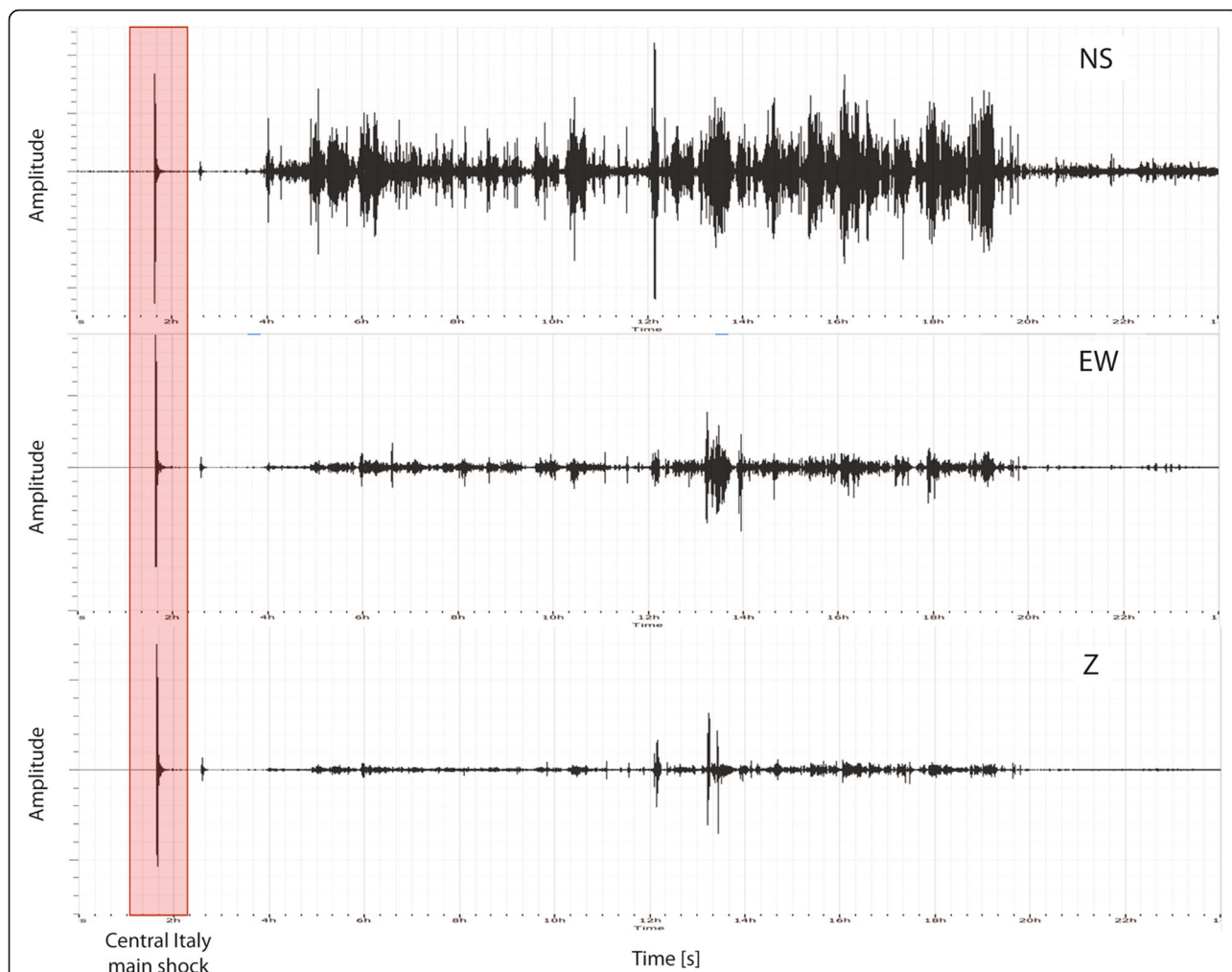


Fig. 9 The August 24, 2016 traces recorded by the Lungarno Torrigiani SVM system: red box highlight the Central Italy earthquake main shock

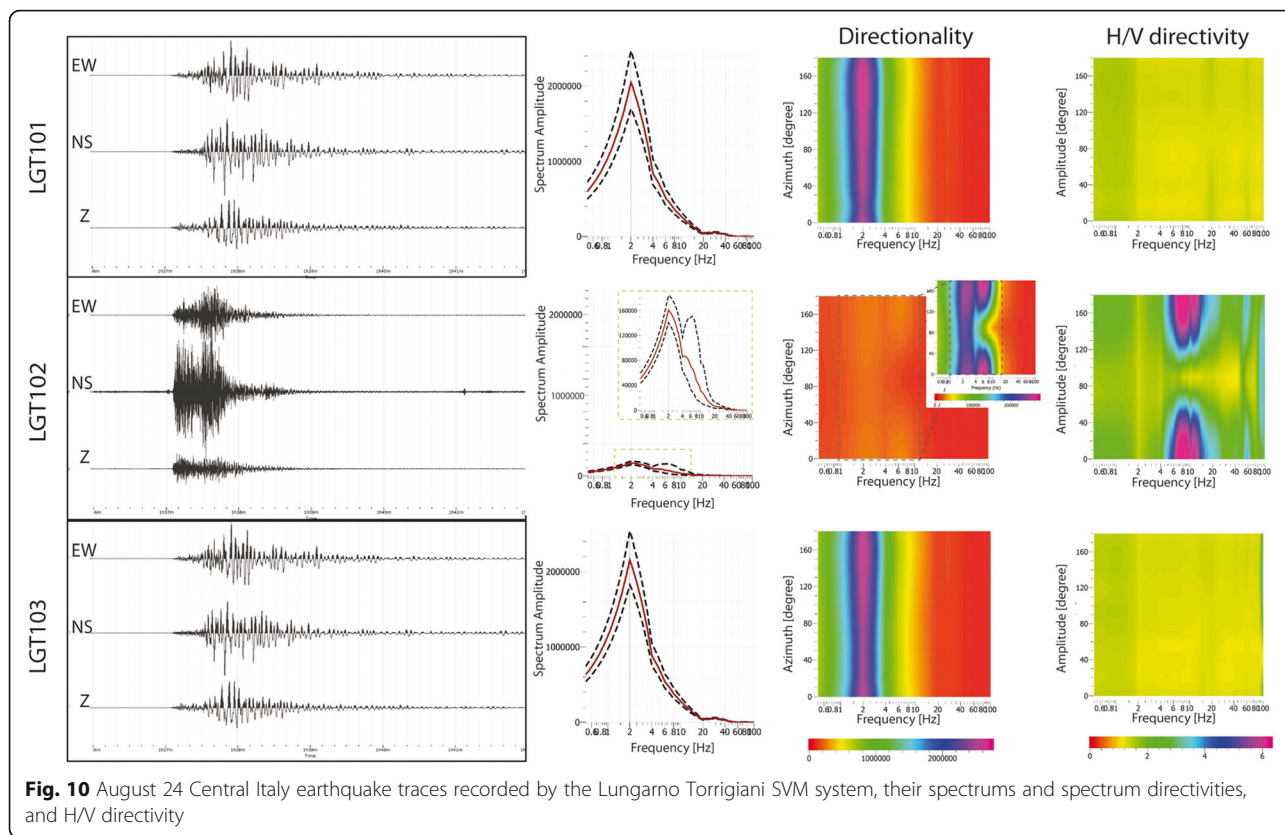
energy content in the 10–20 Hz frequency range, but each one exhibits different frequency peaks. Station LGT101 shows two close peaks at 14 Hz and 18 Hz and another one around 30 Hz; station LGT102 one single peak at 12 Hz, while station LGT103 records a main peak at 16 Hz, and a plateau at higher frequency (20–40 Hz). It is interesting to note that after the end of piling work (Figs. 5–7ii) the spectral content is partially modified, both in amplitude and frequency content, respect to the previous time interval (Figs. 5–7i). Moreover, the LGT102 amplitude (Fig. 6) is much higher (about two times) than the LGT101 and LGT103 amplitude value, that are comparable (Figs. 5–7).

Figure 8 shows the 12-h pcgv values of each component (Fig. 6a: Z, b: NS, and c: EW) at the three stations (green line: LGT101, blue line: LGT102, and yellow line: LGT103). The pcgv values were recorded each time by the station nearest to the working area. They clearly show the work advancement: a) in the first period the three component do not match each other

in terms of recorded peaks; b) in the second time interval the three component, especially at station LGT101, well match each other, because of the vary working procedure, no longer focused perpendicular to the embankment wall (horizontal component NS), but in solicitation of all the components; c) in the last interval the maximum observed velocities definitely drop below 0.5 mm/s at all the components.

On August 24, 2016 at 1:36:32 UTC (3:36:32 local time) a Mw 6.0 earthquake strike central Italy. The epicentre was located in Accumoli (RI) (Lat 42.698 Lon 13.234). Despite the considerable distance from the Lungarno Torrigiani SVM system, about 200 km away, the earthquake waveform is clearly recognizable at each station (Fig. 9). It differs from the signals caused by the ordinary workings in terms of length, spectral content, and also because the solicitation affects all the components.

Figure 10 shows the signals recorded by the three components at each stations during the earthquake



event, the spectrums and their directivity, and the H/V directivity. All the parameters values are comparable for hinge stations LGT101 and LGT103: the energy is focused around 2 Hz and the signal shows directivity neither for the spectrum nor for the H/V. On the other

hand, the cusp station LGT102 shows a spectrum, of a lower amplitude order, with two main peaks (dashed green box in Fig. 10) suggesting that another contribute of energy is focused around 10 Hz. It can easily be seen that it is clearly polarized towards the NS direction,

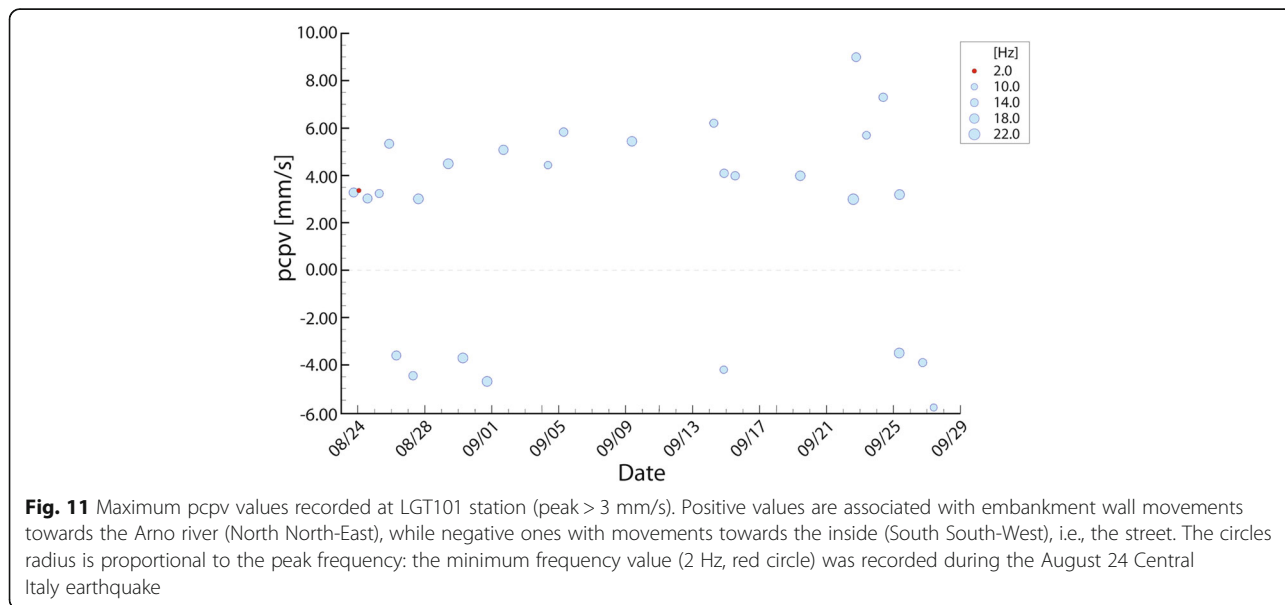


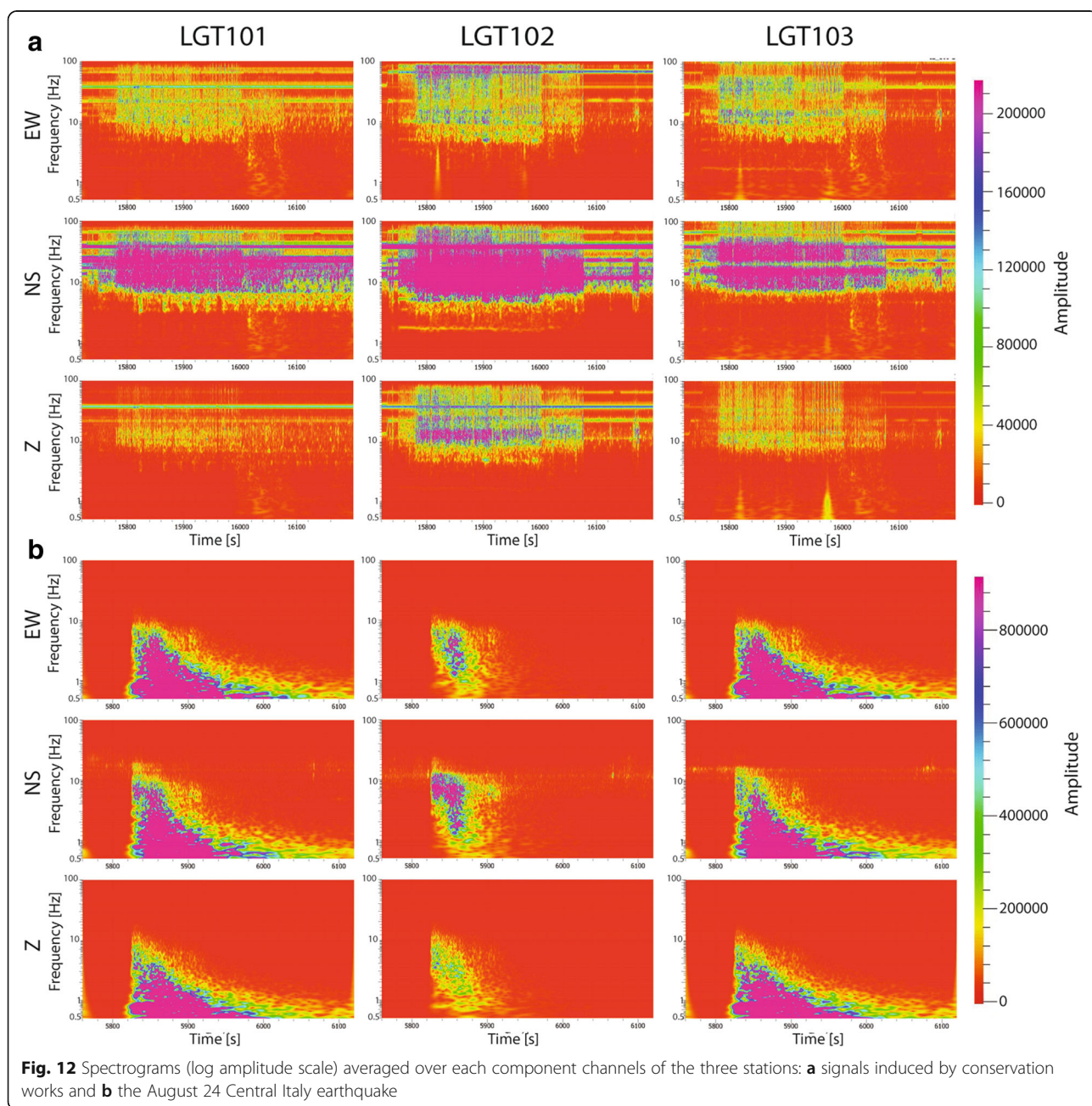
Table 2 Maximum pcgv values recorded on August 24, 2016 at 1:36:32 UTC during the central Italy earthquake

Date and time (local time)	Station	pcgv (mm/s) > 3	Frequency (Hz)
24.08.2016 03:37:49	LGT101	3.38	2
24.08.2016 03:37:49	LGT102	2.00	2
24.08.2016 03:37:50	LGT103	3.50	2

according to the conservation works location, while, also at this station, the 2 Hz peak shows no significant polarization.

Nevertheless, the maximum pcgv values recorded at each station during the earthquake (red dot in Fig. 11) are comparable to those observed during the conservation works (light blue dots in Fig. 11). Finally, in contrast to the other two stations, LGT102 do not recorded velocity > 3 mm/s (Table 2).

In Fig. 12 the running spectrum (RS) shows the time evolution of the frequency content for both the conservation works (Fig. 12a) and earthquake signals



(Fig. 12b); in this figure the spectral amplitude is shown by the coloured scale. The RS frequency content is constant for the signals induced by the conservation works (Fig. 12a), while changes with time for the earthquake signal (Fig. 12b). Moreover, the first type of vibrations shows lower amplitude at the hinge stations (LGT101 – LGT103) and higher at the cusp section, while for the earthquake signal is observed the opposite. This is probably caused by the different damage status at the cusp and at the hinges. It is also worth to note, as already pointed out in this paragraph, that vibrations caused by the conservation works have a higher frequency content (around 10 Hz) than those induced by the earthquake, according to the inelastic attenuation of waves propagating in the Earth with distance, which depends on the frequency (Lay and Wallace 1995).

Conclusions

This paper shows how the H/V technique proved to be a valuable SHM method to estimate the resonant frequency not only of buildings, but also of a squat and monolithic structure like the Lungarno Torrigiani masonry embankment wall. Moreover, this work may contribute to characterize the vibrations induced by piling work at close range, and help to define the maximum acceptable vibration pattern for such structures, since literature is missing of such case studies. The pcpv values clearly showed the work advancement, and the Lungarno Torrigiani SVM indicated that the piling work stressed more the embankment wall section between Ponte alle Grazie hinge and the cusp, since the maximum velocities were recorded by the stations LGT101 and LGT102. The daily pcpv (maximum values along the perpendicular to the wall component) are comparable and sometime higher than those induced by a Mw 6.0 earthquake with an epicentre 200 km far. However, seismic vibration induced by conservation works have a higher frequency content than ones induced by an earthquake.

Finally, comparing 1) the frequency content and amplitude value of the daily recorded signals at each station, 2) the frequency content recorded during a strong earthquake and the daily one, and 3) the response to different kind of stress of the the three structure sectors (the cusp and the two hinges), it can be reasonably said that the riverbank landslide modified the masonry embankment wall natural resonance frequency. Moreover, the hinge zones (corresponding to the stations LGT101 and LGT103) seem to be more sensitive to the vibration characterized by low-frequency content, such as earthquake waveform (as the are high-pass filters), while the cusp section (the most damaged one, where is located

LGT102) is more sensitive to vibration associated with on site works.

Further analysis of the earthquake swarm could provide interesting insights to establish a correlation between the structure sensitivity, earthquake magnitude and epicentre distance.

Abbreviations

DRM: Disaster risk management; DRR: Disaster risk reduction; H/V: Horizontal to vertical spectral ratio; HFA: Hyogo framework for action; pcpv: Peak component particle velocity; RS: Running Spectrum; SFDRR: Sendai framework for disaster risk reduction; SHM: Structural health monitoring; SVM: Seismic vibration monitoring; UNESCO: United Nations Educational, Scientific and Cultural Organization

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Authors' contributions

VP, AL, LL, and MN contributed to the fieldwork, and were responsible for the collecting field data and their integration and interpretation, as well as the preparation of the manuscript. PC gave technical support and conceptual advice, and contribute to the preparation of the manuscript. NC supervised the project. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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References

- Aguilar, R., R. Marques, K. Sovero, C. Martel, F. Trujillano, and R. Boroschek. 2015. Investigations on the structural behaviour of archaeological heritage in Peru: from survey to seismic assessment. *Engineering Structures* 95: 94–111. doi: <http://dx.doi.org/10.1016/j.engstruct.2015.03.058>.
- Alcantara-Ayala, I. 2002. Geomorphology, natural hazards, vulnerability and prevention of natural disasters in developing countries. *Geomorphology* 47: 107–124. [http://dx.doi.org/10.1016/S0169-555X\(02\)00083-1](http://dx.doi.org/10.1016/S0169-555X(02)00083-1).
- Asteris, P.G., and V. Plevris. 2015. Handbook of research on seismic assessment and rehabilitation of historic structures. In *Advance in civil and industrial engineering book series*. USA: Hershey.
- Asteris, P.G., Chronopoulos, M.P., Chrysostomou, C.Z., Varum, H., Plevris, V., Kyriakides, N., Silva, V. 2014. Seismic vulnerability assessment of historical masonry structural systems. *Engineering Structures* 62–63:118–134.
- Aven, T. 2010. On how to define, understand and describe risk. *Reliability Engineering and System Safety* 95: 623–631. doi: <http://dx.doi.org/10.1016/j.res.2010.01.011>.
- Barbieri, G., L. Biolzi, M. Bocciarelli, L. Fregonese, and A. Frigeri. 2013. Assessing the seismic vulnerability of historical building. *Engineering Structures* 57: 523–535. doi:<http://dx.doi.org/10.1016/j.engstruct.2013.09.045>.
- Bartolini, C., and G. Pranzini. 1981. Plio-quadernary evolution of the Arno basin drainage. *Zeitschrift für Geomorphologie* 40: 77–91. Suppl., BD.
- Binda, L., C. Modena, F. Casarin, F. Lorenzoni, L. Cantini, and S. Munda. 2011. Emergency actions and investigations on cultural heritage after the L'Aquila earthquake: the case of the Spanish Fortress. *Bulletin of Earthquake Engineering* 9: 105–138.
- Boccaletti, M., G. Corti, P. Gasperini, L. Piccardi, G. Vannucci, and S. Clemente. 2001. Active tectonics and seismic zonation of the urban area of Florence, Italy. *Pure and Applied Geophysics* 158: 2313–2332. doi:<http://dx.doi.org/10.1007/PL00001172>.
- Cardona, O.D. 2004. The need for rethinking the concepts of vulnerability and risk from a holistic perspective: a necessary review and criticism for effective

- risk management. In: Bankoff G, Frerks G, Hilhorst D (eds.) London: Mapping Vulnerability: Disasters, Development and People, Earthscan.
- Carniel, R., F. Barazza, and P. Pascolo. 2006. Improvement of Nakamura technique by singular spectrum analysis. *Soil Dynamics and Earthquake Engineering* 26: 55–63.
- Casolo, S., G. Milani, G. Uva, and C. Alessandri. 2013. Comparative seismic vulnerability analysis on ten masonry towers in the coastal Po Valley in Italy. *Engineering Structures* 49: 465–490.
- Castellaro, S., S. Imposa, F. Barone, F. Chiavetta, S. Gresta, and F. Mulargia. 2008. Georadar and passive seismic survey in the roman amphitheatre of Catania (Sicily). *Journal of Cultural Heritage* 9: 357–366. doi:10.1016/j.culher.2008.03.004.
- Ceravolo, R., G. Pistone, L. Zanotti Fragonara, S. Massetto, and G. Abbiati. 2014. Vibration-based monitoring and diagnosis of cultural heritage: a methodological discussion in three examples. *International Journal of Architectural Heritage* 10: 375–395. doi:10.1080/15583058.2013.850554.
- Chang, P.C., A. Flatau, and S.C. Liu. 2003. Review paper: health monitoring of civil infrastructure. *Structural Health Monitoring* 2: 257–267. doi:10.1177/145792103036169.
- Del Gaudio, V., S. Coccia, J. Wasowski, M.R. Gallipoli, and M. Mucciarelli. 2008. Detection of directivity in seismic site response from microtremor spectral analysis. *Natural Hazards and Earth System Sciences* 8: 751–762.
- Del Gaudio, V., S. Muscillo, and J. Wasowski. 2014. What we can learn about slope response to earthquake from ambient noise analysis: an overview. *Engineering Geology* 182: 182–200. doi:10.1016/j.enggeo.2014.05.010.
- Del Soldato, M., S. Segoni, P. De Vita, V. Pazzi, V. Tofani, S. Moretti, et al. 2016. Thickness model of pyroclastic soils along mountain slopes of Campania (southern Italy). In *Landslides and engineered slopes. Experience, theory and practice*, ed. A. Aversa. Rome: Associazione Geotecnica Italiana.
- Diaferio, M., Foti, D., Giannoccaro, N.I. 2015a. Ambient vibration testing and operational modal analysis of a historic tower. *Recent Advances in Mechanics, Mechatronics and Civil, Chemical and Industrial Engineering*. 25–30. ISBN: 978-1-61804-325-2. <http://www.inase.org/library/2015/zakynthos/bypaper/CIMC/CIMC-03.pdf>.
- Diaferio, M., Foti, D., Giannoccaro, N.I. 2015b. Identification of the modal properties of a squat historic tower for the tuning of FE model. Proceedings of the 6th International Operational Modal Analysis Conference.
- Doornkamp, J.C. 1989. Hazards. In *Earth science mapping for planning, development and conservation*, ed. G.J.H. McCall and B.R. Marker. London: Graham & Trotman.
- Fäh, D., F. Kind, and D. Giardini. 2001. A theoretical investigation of average H/V ratios. *Geophysical Journal International* 145: 535–549.
- Fedeski, M., and J. Gwilliam. 2007. Urban sustainability in the presence of flood and geological hazards: the development of a GIS-based vulnerability and risk assessment methodology. *Landscape and Urban Planning* 83: 50–61. doi:<http://dx.doi.org/10.1016/j.landurbplan.2007.05.012>.
- Fiaschi A, Matassoni L, Pratesi G, Garzonio CA, Malesani P. 2012. Microtremor analysis of the Basilica of the Holy Sepulchre, Jerusalem. *Soil Dyn Earthq Eng* 41:14-22. doi:<http://dx.doi.org/10.1016/j.soildyn.2012.05.00>.
- Herak, M. 2008. The use of ambient noise for building and soil characterization. In *Increasing seismic safety by combining engineering technologies and seismological data, NATO science for peace and security, series C: environmental security*, ed. M. Mucciarelli, M. Herak, and J. Cassidy. Netherlands: Springer.
- Jigyasu R, Murthy M, Boccardi G, Marrion C, Douglas D, King J, O'Brien G, Dolcemascolo G, Kim Y, Albrito P, Osihn M. 2013. Heritage and resilience: issues and opportunities for reducing disaster risks. Fourth session of the Global Platform on Disaster Risk Reduction (http://nrl.northumbria.ac.uk/17231/1/Heritage_and_Resilience_Report_for_UNISDR_2013.pdf)
- Lacanna, G., M. Ripepe, E. Marchetti, M. Coli, and C.A. Garzonio. 2016. Dynamic response of the baptistery of San Giovanni in Florence, Italy, based on ambient vibration test. *Journal of Cultural Heritage* 20: 632–640. doi:<http://dx.doi.org/10.1016/j.culher.2016.02.007>.
- Larose, E., S. Carrière, C. Voisin, P. Bottelin, L. Baillet, P. Guéguen, F. Walter, D. Jongmans, B. Guillier, S. Garambois, F. Gimbert, and C. Massey. 2015. Environmental seismology: what can we learn on earth surface processes with ambient noise? *Journal of Applied Geophysics* 116: 62–74. doi:10.1016/j.apgeo.2015.02.001.
- Lay, T., and T.C. Wallace. 1995. *Modern global seismology*. New York: Academic.
- Lekkas, E.L. 2000. *Natural and technological catastrophes*. Athens: Access Prepress.
- Lermo, J., and F.J. Chavez-Garcia. 1993. Site effect evaluation using spectral ratios with only one station. *Bulletin of the Seismological Society of America* 83: 1574–1594.
- Lermo, J., and J. Chavez-Garcia. 1994. Are microtremors useful in site response evaluation? *Bulletin of the Seismological Society of America* 84: 1350–1364.
- Lotti, A., G. Saccorotti, A. Fiaschi, L. Matassoni, G. Gigli, V. Pazzi, N. Casagli, et al. 2015. Seismic monitoring of rockslide: the torgiannetto quarry (central apennines, italy). In *Engineering geology for society and territory – Vol. 2*, ed. G. Lollino, 1537–1540. Switzerland: Springer International Publishing. doi:10.1007/978-3-319-09057-3_272.
- McCall, G.J.H. 1992. Natural and man-made hazards: their increasing importance in the end-20th century world. In *Geohazards natural and man-made*, ed. G.J. H. McCall, D.J.C. Laming, and S.C. Scott, 1–4. London: Chapman & Hall.
- Morelli, S., S. Segoni, G. Manzo, L. Ermini, and F. Catani. 2012. Urban planning, flood risk and public policy: the case of the Arno river, Firenze, Italy. *Applied Geography* 34: 205–218. doi:10.1016/j.apgeog.2011.10.020.
- Morelli, S., A. Battistini, and F. Catani. 2014. Rapid assessment of flood susceptibility in urbanized rivers using digital terrain data: application to the Arno river case study (Firenze, northern Italy). *Applied Geography* 54: 35–53. doi:10.1016/j.apgeog.2014.06.032.
- Nakamura, Y. 1989. A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. *Quarterly Report of the Railway Technical Research Institute* 30: 25–33.
- Pazzi, V., S. Morelli, F. Fidolini, E. Krymi, N. Casagli, and R. Fanti. 2016a. Testing cost-effective methodologies for flood and seismic vulnerability assessment in communities of developing countries (Dajç northern Albania). *Geomatics, Natural Hazards and Risk* 7: 971–999. doi:10.1080/19475705.2015.1004374.
- Pazzi, V., S. Morelli, F. Pratesi, T. Sodi, L. Valori, L. Gambacciani, and N. Casagli. 2016b. Assessing the safety of schools affected by geo-hydrologic hazards: the geohazard safety classification (GSC). *International Journal of Disaster Risk Reduction* 15: 80–93. doi:<http://dx.doi.org/10.1016/j.ijdr.2015.11.006>.
- Pazzi, V., D. Tapete, L. Cappuccini, and R. Fanti. 2016c. An electric and electromagnetic geophysical approach for subsurface investigation of anthropogenic mounds in an urban environment. *Geomorphology* 273: 335–347. doi: <http://dx.doi.org/10.1016/j.geomorph.2016.07.035>.
- Pazzi, V., Tanteri, L., Bicchocchi, G., D'Ambosio, M., Caselli, A., Fanti, R. 2016d. H/V measurements as an effective tool for the reliable detection of landslide slip surfaces: case studies of Castagnola (La Spezia, Italy) and Roccalbegna (Grosseto, Italy). *Physics and Chemistry of the Earth*. doi:<http://dx.doi.org/10.1016/j.pce.2016.10.014>. In press.
- Ramos, L.F., L. Marques, P.B. Lourenço, G. De Roeck, A. Campos-Costa, and J. Roque. 2010. Monitoring historical masonry structures with operational modal analysis: two case studies. *Mechanical systems and signal processing* 24: 1291–1305. doi:<http://dx.doi.org/10.1016/j.ymssp.2010.01.011>.
- Romão, X., E. Paupério, and N. Pereira. 2016. A framework for the simplified risk analysis of cultural heritage assets. *Journal of Cultural Heritage* 20: 696–708. doi:<http://dx.doi.org/10.1016/j.culher.2016.05.007>.
- Russo, S. 2013. On the monitoring of historic anime sante church damaged by earthquake in L'Aquila. *Structural Control and Health Monitoring* 20: 1226–1239. doi:10.1002/stc.1531.
- SESAME. 2004. Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations. Measurements, processing and interpretation. SESAME European research project, WP12 – Deliverable D23. 12, European Commission – Research General Directorate, Project No. EVG1-CT-2000-00026 SESAME. <ftp://ftp.geo.uib.no/pub/seismo/SOFTWARE/SESAME/USERGUIDELINES/SESAME-HV-User-Guidelines.pdf>.
- Stewart, P.J., and G. Fenves. 1998. System identification for evaluating soil-structure interaction effects in buildings from strong motion recordings. *Earthquake Engineering and Structural Dynamics* 27: 869–885.
- Tapete, D., N. Casagli, G. Luzzi, R. Fanti, G. Gigli, and D. Leva. 2013. Integrating radar and laser-based remote sensing techniques for monitoring structural deformation of archaeological monuments. *Journal of Archaeological Science* 40: 176–189. doi:<http://dx.doi.org/10.1016/j.jas.2012.07.024>.
- Zulherman, M.S., A. Yaakup, and J. Wongso. 2006. GIS base modeling of the flood impacts on the urban development. In *Paper presented*. Kuala Lumpur: International Conference on Construction Industry 2006: Toward Innovative Approach in Construction and Property Development.