Dynamic monitoring of a tunnel-like masonry structure via WSN

Gianni Bartoli,

Department of Civil and Environmental Engineering.
University of Florence, Florence I-50139, Italy
Email: gianni.bartoli@unifi.it
http://orcid.org/0000-0002-5536-3269

Michele Betti,

Department of Civil and Environmental Engineering.
University of Florence, Florence I-50139, Italy
Email: michele.betti@unifi.it
http://orcid.org/0000-0002-8389-3355

Maria Girardi,

National Research Council of Italy (CNR),
Institute of Information Science and Technologies “A. Faedo” Via G. Moruzzi, 1, San Cataldo 56124 Pisa, Italy
Email: maria.girardi@isti.cnr.it
http://orcid.org/0000-0002-7358-5607

Cristina Padovani,

National Research Council of Italy (CNR),
Institute of Information Science and Technologies “A. Faedo” Via G. Moruzzi, 1, San Cataldo 56124 Pisa, Italy
Email: cristina.padovani@isti.cnr.it
http://orcid.org/0000-0002-2467-569X

Daniele Pellegrini,

National Research Council of Italy (CNR),
Institute of Information Science and Technologies “A. Faedo” Via G. Moruzzi, 1, San Cataldo 56124 Pisa, Italy
Email: daniele.pellegrini@isti.cnr.it
http://orcid.org/0000-0002-3416-771X

Giacomo Zini,

Department of Civil and Environmental Engineering.
University of Florence, Florence I-50139, Italy
Email: giacomo.zini@unifi.it
http://orcid.org/0000-0003-3772-2472

Abstract

This paper reports an application of wireless sensor network technology to the long-term monitoring of a historic masonry tunnel-like structure located in Italy. The monitoring was performed within the activity of a research project aimed at providing a general framework to check the structural health of heritage structures and to real-time detect any potential damage that may compromise their safety. The tunnel-like structure was selected being, to the best of authors' knowledge, a challenging experiment both for the type of structure itself and for the technical solution to be employed for installing the monitoring system. This paper, after a brief description of the installed monitoring system and the design of the sensor layout, summarizes the lesson learned after one year of monitoring.

Keywords

Long-term Monitoring, tunnel-like masonry structure; Cultural Heritage, Dynamic Identification, Wireless Sensor Networks.

1. Introduction

The increasing ageing of the building stock asks today for effective and reliable management protocols (van Breugel, 2017). Such protocols should include a long-term continuous monitoring system characterized by resilience to adverse weather conditions, low visual impact, moderate installation and maintenance costs, robust algorithms for data analysis, and efficient and automated systems for the storage and management equipped with remote access (Noel et al., 2017; Warsi et al., 2019). Many of these requirements are fulfilled by using wireless sensor networks (WSN) coupled with micro-mechanical sensors (MEMS). These technologies allow reducing the global cost and visual impact of the monitoring system, thus facilitating long-term structural health monitoring programs.

Although the first examples of the use of WSN date back to fifteen years ago (Kim et al., 2007; Zonta et al., 2010), their application for long-term monitoring still presents many open issues. These are related to the significant amount of data gathered during measurements, which should have high sampling frequency (typically from 50 Hz henceforth), the consequent high energy consumption, and the choice of the sensors' optimal placement on large-size structures. Real-world examples of WSN for SHM are typically installed on bridges (Noel et al., 2017), public structures and buildings (Liaw et al., 2020). Concerning architectural heritage, the use of WSN for structural health monitoring applications is still limited to some pioneering examples (Zonta et al., 2010; Potenza et al., 2015; Clementi et al., 2018; D'alessandro et al., 2019; Barsocchi et al., 2020). On the contrary, the safeguarding of heritage structures is a promising application field for WSN technologies, especially in consideration of their low invasiveness.

Long-term monitoring protocols carried out on ancient buildings and monuments have demonstrated to bring about numerous and significant advantages (Ramos et al., 2010; Gentile et al., 2016; Cavalagli et al., 2017; Azzara et al., 2019). They allow recording the structural response to environmental and anthropic actions, as well as to exceptional events such as earthquakes or extreme weather conditions. Since in the case of heritage buildings this response is hard to be reliably predicted via numerical simulation only (due to lack of information on the actual arrangement of materials, loads, building construction phases and techniques), the combined use of data from a long-term monitoring with numerical simulation allows more effective predictions of the structural behaviour of these structures (Ubertini et al., 2017; Lacanna et al., 2020). Moreover, the analysis of the massive amount of data coming from long-term monitoring makes it possible to develop damage detection procedures and identify damage levels and thresholds for the monitored structure (Comanducci et al., 2016).

This paper reports the results of a long-term dynamic monitoring conducted via WSN on a masonry tunnel-like structure located in Livorno (Italy): the “Voltone”. The monitoring was carried out in the framework of the research project MOSCARDO (ICT technologies for structural monitoring of Ancient Constructions based on wireless sensor networks and drones; http://www.moscardo.it), funded by the Region of Tuscany and the Italian Ministry of Education and Research. The project was aimed at designing, developing, and testing new tools for structural health monitoring, including networks of wireless sensors able to operate in both ordinary and emergency conditions for long-term monitoring purposes. The experiment conducted on the tunnel-like structure was challenging, both for the type of structure itself and for the difficulty of installing the monitoring system. To the best of authors’ knowledge, no similar experiences are reported in the literature.

This paper is organized as follows. Section 2 reports a brief description of the “Voltone”. Section 3 describes a short-term monitoring system composed of traditional piezoelectric accelerometers installed in October 2017. This system worked for two days and was employed to design the layout of the long-term network of wireless sensors. The results of this initial measurement campaign are reported and discussed. Section 4 reports the long-term MOSCARDO wireless monitoring system. This system was set confirming the accelerometers layout adopted in 2017. Two linear displacement transducers were in addition employed to monitor a crack located on the northern side of the structure; some environmental parameters such as temperature and humidity were measured as well. The system ran from November 2018 until December 2019, when it was removed according to the project work plan. The analysis of data recorded by the MOSCARDO system is described in Section 5, where the main measurements (accelerations and crack widths) are reported, together with their variation over the monitoring year.

2. Case study

This paper is focused on the “Voltone” (i.e. big vault), a 220-meter long vaulted masonry tunnel located under Piazza della Repubblica (Republic Square) in Livorno (Figure 1) and subject to traffic vibrations coming from the overlying streets, running around the square. The square (about 18000 m^2) and the tunnel were built in the first half of the nineteenth century by the architect Luigi Bettarini, under the government of Leopoldo II d’Asburgo-Lorena (Bellinazzi and Contini, 2002), by burying a large area of the so-called “Fosso Reale” (Real Canal) and channelling the water under the tunnel.

As a result of this impressive engineering endeavour, the “Voltone” closed the perimeter of the so-called Buontalenti’s Pentagon, a canals network in pentagonal shape which encloses the old town of Livorno since the XVI century.

The “Voltone” is a masonry structure constituted by a segmental masonry vault spanning about 12.5 m and standing on two lateral walls, through which the “Fosso Reale” flows. The structure’s walls, made up by external layers of a local chalky and an inner cohesive mortar core layer, are about 2.3 m thick and are variable in height above the surface of the canal, decreasing from 5.27 m at the southern side to 2.65 m at the northern. The overall maximum height of the walls is 9.3 m; they are strengthened by buttresses placed at intervals of about 5.8 meters one from the others.

Figure 1. Piazza della Repubblica, Livorno (Tuscany, Italy). The southern entrance of the "Voltone" is visible in the lower part of the image. The white dashed lines indicate the underground tunnel-like structure.

In the past years, a survey of the structure including laser scanner digital acquisition, geo-radar tests and masonry coring allowed acquiring the outer geometry of the structure, as well as thickness and stratigraphy of the vault and the walls (Girardi et al., 2015). The ends of the vault, whose thickness is about 0.7 m, support some trafficked roadways ("Viale degli Avvalorati" in the northern side and "Via del Voltone" in the southern), while the central part of the structure – about 0.4 m thick - supports the square, which is reserved to pedestrians. The vault is made up of lime mortar and bricks.

3. Sensor layout design

A two-days set-up test aimed at measuring the vibrations of the vault under the square was performed on 4 and 5 October 2017 by using high-sensitive piezoelectric accelerometers. This test was planned with the aim to perform a dynamic identification of the structure, and thus facilitate the design and optimal placement of the permanent monitoring system. Eleven mono-axial and two bi-axial piezoelectric accelerometers (type PCB393C and PCB393B31) were installed at the intrados of the vault and the lateral walls in the southern part of the structure following the sensor layout shown in Figure 2.

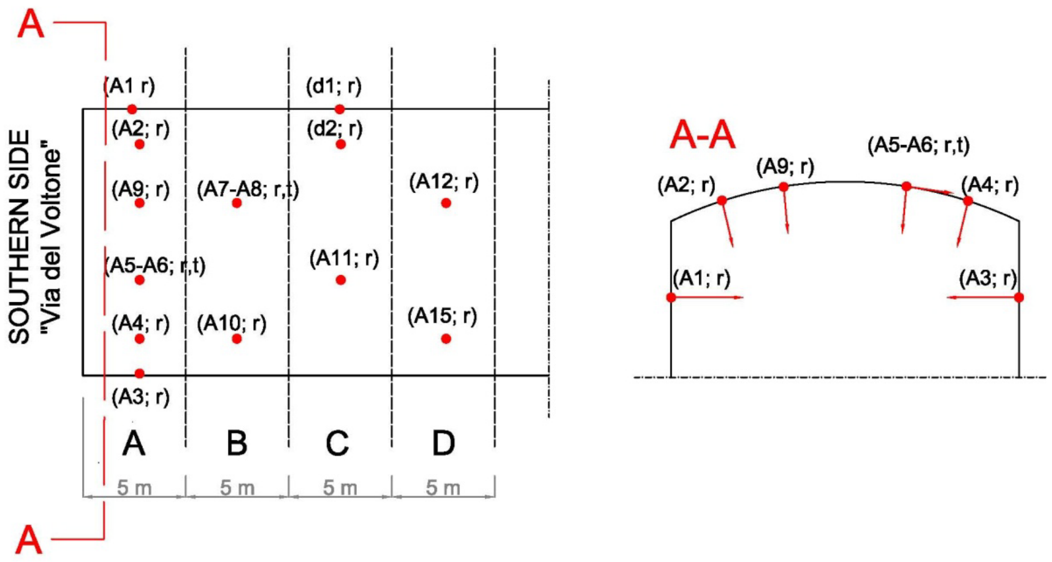
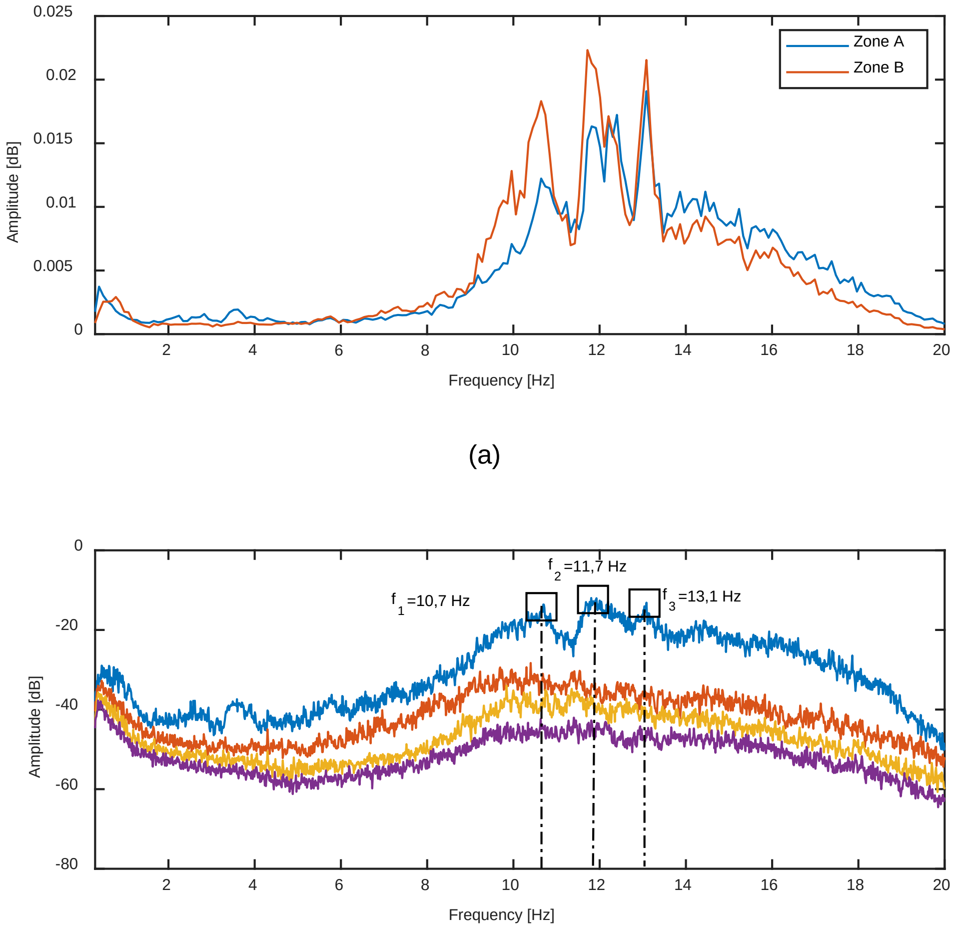


Figure 2. Sensors layout of the two-days set-up test.

The instrumented part of the structure was divided into four areas, each 5 m wide, starting from the southern entrance (A area) and going inwards. The first two areas (A and B) are located under the roadways of “Via del Voltone”, the remaining two (C, D) under “Piazza della Repubblica”. The dynamic response of the structure was acquired via 30 measurements at a sampling frequency of 400 Hz. The mono-axial sensors recorded in the radial direction (with respect to the intrados of the gallery), while the bi-axial devices recorded in the radial and tangential directions. The length of the records was about ten minutes, with a maximum length of one hour. A camera was put on the square to record the traffic on “Via del Voltone”.

Figure 3a shows the Average Normalized Power Spectral Densities (ANPSD) of the radial components in the vault for the two areas located immediately below the vehicular traffic. The signals were preliminary processed via a band-pass (0.3 – 20 Hz) fourth-order Butterworth filter and down-sampled to 50 Hz. Some peaks are visible in the interval 10 Hz -15 Hz, but the traffic vibrations and the damping effect of the infill over the vault determine the large-band dispersion as highlighted in the figure.



(a)

(b)

Figure 3. (a) Average Normalized Power Spectral Density (ANPSD) for the radial components of the signal in the vault. (b) The first four singular values of the Power Spectral Density (PSD) matrix and the values of three identified natural frequencies.

The interaction between the structure's dynamics and the traffic-induced vibrations leads to challenging issues in the modal identification. In spite of that, the peaks identified in Figure 3a can also be found via Frequency Domain Decomposition (FDD) (Brincker et al., 2001), as shown in Figure 3b, where the first four singular values (evaluated on the signals recorded by all the sensors) are plotted. Three peaks are visible in the frequency band 10 - 15 Hz (excited by the frequency content of the traffic) and almost coincide with those shown in Figure 3a.

Sensor A7, placed in the B area (Figure 2), recorded the maximum energy signal. This area corresponds to the inner roadway of "Via del Voltone", which turned out to be the most trafficked during the day. Examining signals recorder by sensor A7 allows us to get some information about the effects of the traffic on the dynamic response of the structure.

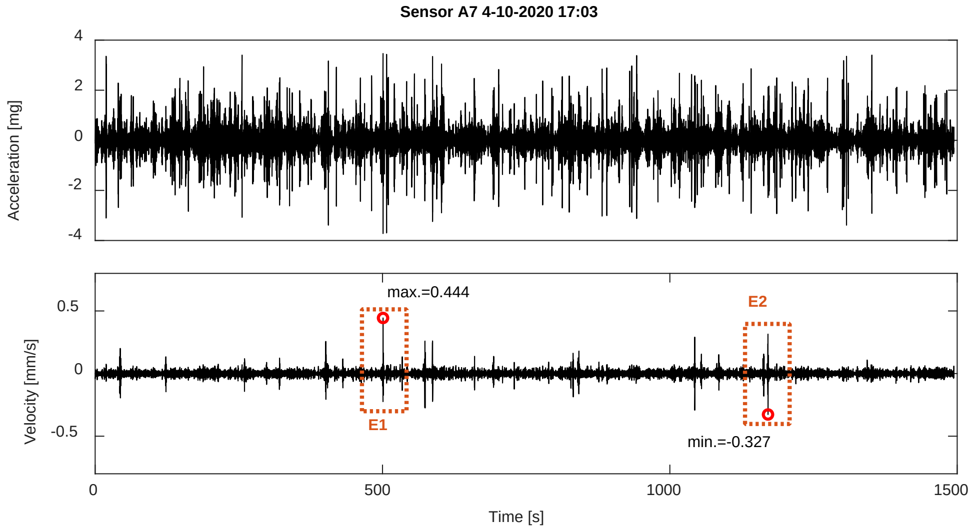
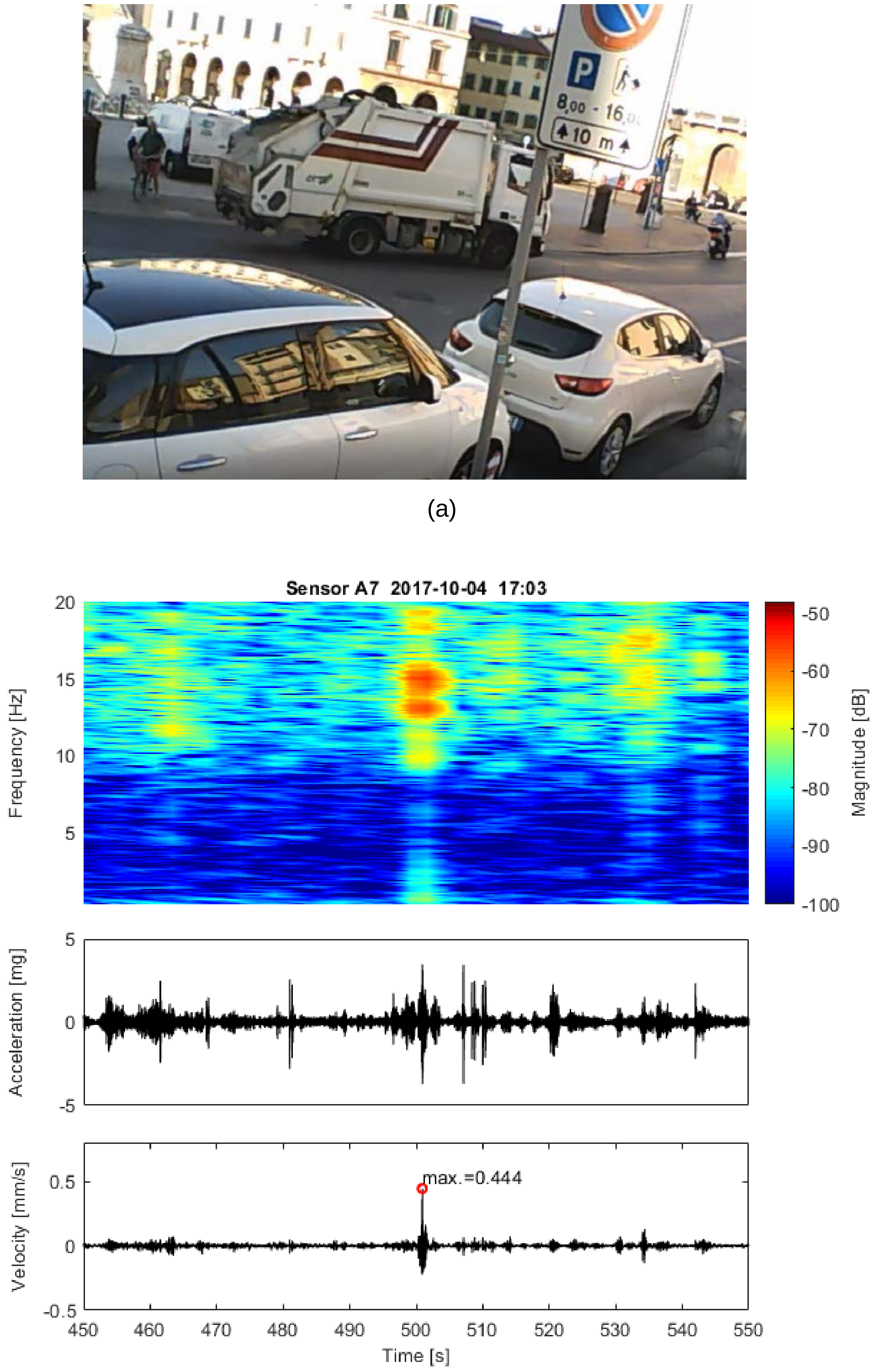


Figure 4. Acceleration recorded by sensor A7 and the corresponding peak component particle velocity (PCPV) obtained by integration over the time domain.

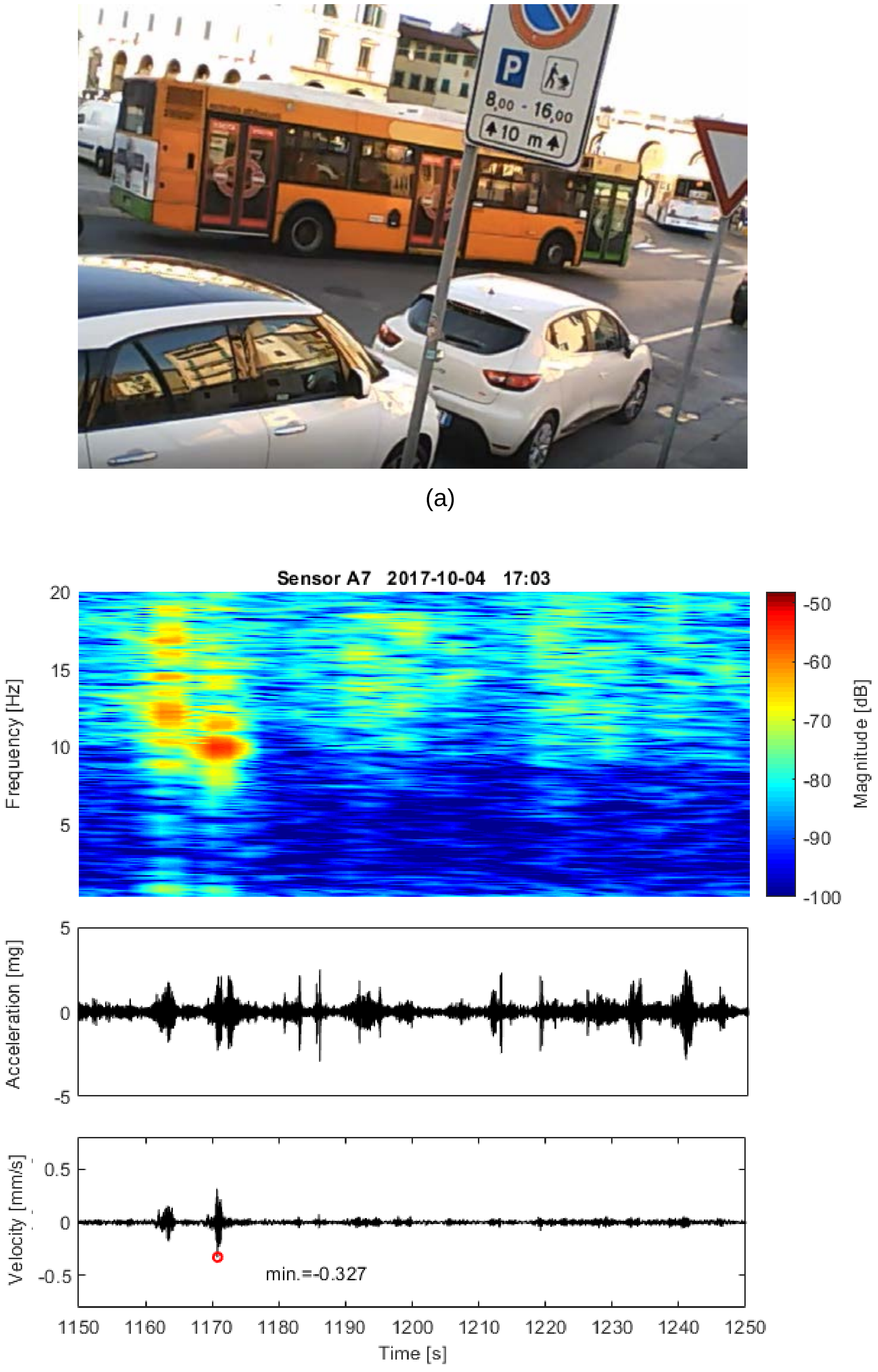
According to the Italian code UNI 9916:2014 (UNI 9916:2014), a useful parameter to check the possible damage induced on the structure by traffic vibrations is the so-called peak component particle velocity (PCPV). Figure 4 shows the PCPV of sensor A7, obtained by filtering one of the acceleration records via a high-pass sixth-order Butterworth filter with a cut-off frequency of 1 Hz and successively integrating over the time domain. Two different events (named E1 and E2 in Figure 4) reported the maximum and the minimum values of PCPV. Time-frequency analysis was performed via Short Fourier Transform (SFT) to obtain more information on the vibrations induced by these events.



(a)

(b)

Figure 5. Event E1: (a) Passage of a garbage truck over the vault (the camera is installed over “Via del Voltone”) and (b) spectrogram of the signal.



(a)

(b)

Figure 6. Event E2: (a) Passage of a bus over the vault (the camera is installed over “Via del Voltone”) and (b) spectrogram of the signal.

The results of this analysis are shown in Figure 5 (event E1), and Figure 6 (event E2); the energy peaks correspond to the frequency band identified in Figure 3, confirming the presence of the resonant frequencies shown in Figure 3. Furthermore, it is worth noting that the vehicle speed plays an important role on the PCPV; in fact, visual inspection of the videos recorded on the square revealed that the garbage truck was faster than the bus. Correspondingly, despite the lower weight, the dynamic effect of the truck on the vault results more evident than that of the bus, thus confirming the model proposed by Watts (Watts 1990). Concluding, the results of the dynamic test performed on the structure can be summarized as follows:

- the PCPV peaks correspond to the passage of heavy-vehicles (bus or trucks) and are influenced by the vehicle speeds;
- the PCPV values are largely lower than the limit of 2.5 mm/s recommended by the UNI 9916:2014; this suggests not to collect these values during the long-term continuous monitoring;
- the traffic-induced vibrations mainly excite the frequency band 10 - 15 Hz, where some structural mode shapes can be identified;
- the preliminary sensors’ layout seems able to characterize the dynamic response of the masonry tunnel; it was therefore confirmed for the long-term network of wireless sensors.

4. MOSCARDO monitoring system

4.1. The MOSCARDO system

The MOSCARDO system developed during the homonymous project is targeted at Local Agencies of the Ministry of Cultural Heritage and Activities, Local and Regional Administrations, Civil Protection and all the authorities and organizations responsible for the architectural heritage safeguard. MOSCARDO (www.moscardo.it) is a scalable and flexible system, which can be easily deployed on buildings and infrastructures. It encompasses a Monitoring Control Centre (MCC) collecting and analysing data coming from the sensor networks deployed on the construction of interest. Unmanned Aerial Vehicles (UAVs) can also be used for visual inspection, providing a dedicated video feed to both close and remote operators. In particular, the MOSCARDO system is composed of:

- integrated Wireless Sensor Networks (WSNs) for the acquisition of structural and environmental data, providing a low cost, high resolution and limited visual impact monitoring system;
- flexible and reliable IoT communication infrastructure built upon a publish/subscribe communication paradigm;
- Monitoring Control Centre (MCC) designed according to a cloud architecture that provides services for storage, processing, and interpretation of data coming from the WSNs;
- algorithms and models for the analysis of the collected data and the numerical simulation of the dynamic behaviour of monitored structures;
- multi-channel and multi-platform interfaces for accessing and analysing data, images and videos, so to promptly notify the events of interest captured by the monitoring system;
- front-end Augmented Reality (AR) for the interactive display of video streams and data collected by the deployed sensors day by day, during drone inspections, and for offline displaying the 3D model of the structure in an immersive setup.

Apart from the “Voltone” in Livorno, the MOSCARDO system, was installed on the “Torre Grossa” in San Gimignano and on the “Torre di Matilde” in Livorno. Some results obtained on the “Torre di Matilde”, a medieval tower located in the “Fortezza Vecchia” (Old Fortress), are shown in Barsocchi et al. (2020), together with a detailed description of the hardware components of the monitoring system.

4.2. Long-term WSN

The permanent monitoring network installed on the “Voltone” consists of twenty-two transducers (eleven mono-axial accelerometers, two bi-axial accelerometers, two linear displacement transducers for crack monitoring, a thermometer installed nearby the displacement transducers, and two weather control units for temperature and humidity, installed in the tunnel and on the square) grouped in sixteen sensor nodes. Figure 7a shows the installation operations and Figure 7b the final layout of the sensors in the southern end of the vault. The presence of the canal, the height of the vault under the water level and the number of different authorities involved in the maintenance and governance of the structure made the operations particularly challenging.

The overall sensor layout is reported in Figure 8; all the accelerometers measure in the radial direction with respect to the intrados of the tunnel, except for two bi-axial sensors (n. 1023 and n. 1026 in Figure 8), which measure both in radial and tangential directions.

The accelerometers, designed and produced by the enterprises involved in the MOSCARDO project, were assembled by using Micro-Electro-Mechanical Systems (MEMS) transducers, to reduce the cost of the network. In particular, “Colybris VS1002” transducers were employed and allowed a good compromise between price and performances. “Gefran PZ67” auto-aligning potentiometric transducers were instead employed to detect the crack amplitudes in the northern side of the structure, while temperature and humidity were measured via devices produced by Devis s.r.l.

(a)

(b)

Figure 7. Long-term monitoring system: installation of the sensors (a) and final layout of the sensors in the southern end of the vault (b).

The accelerometer sensors recorded fifteen minutes per hour, at a sampling frequency of 50 Hz, while the environmental sensors acquired one sample per hour. All devices of the sensor network were connected on-site to the power supply. The sensors were connected and synchronised through wireless networks and all the records sent to an on-line database (Monitoring Control Centre, MCC, https://ccm.moscardo.it/), where data were stored and accessible by the researchers of the MOSCARDO project and the technicians in charge with the maintenance of the structure. Fast visualization of the measured quantities and preliminary processing were also allowed by the system. The system was installed in November 2018 and ran until December 2019, as scheduled in the project work plan. During one year of continuous monitoring, several blackouts occurred.

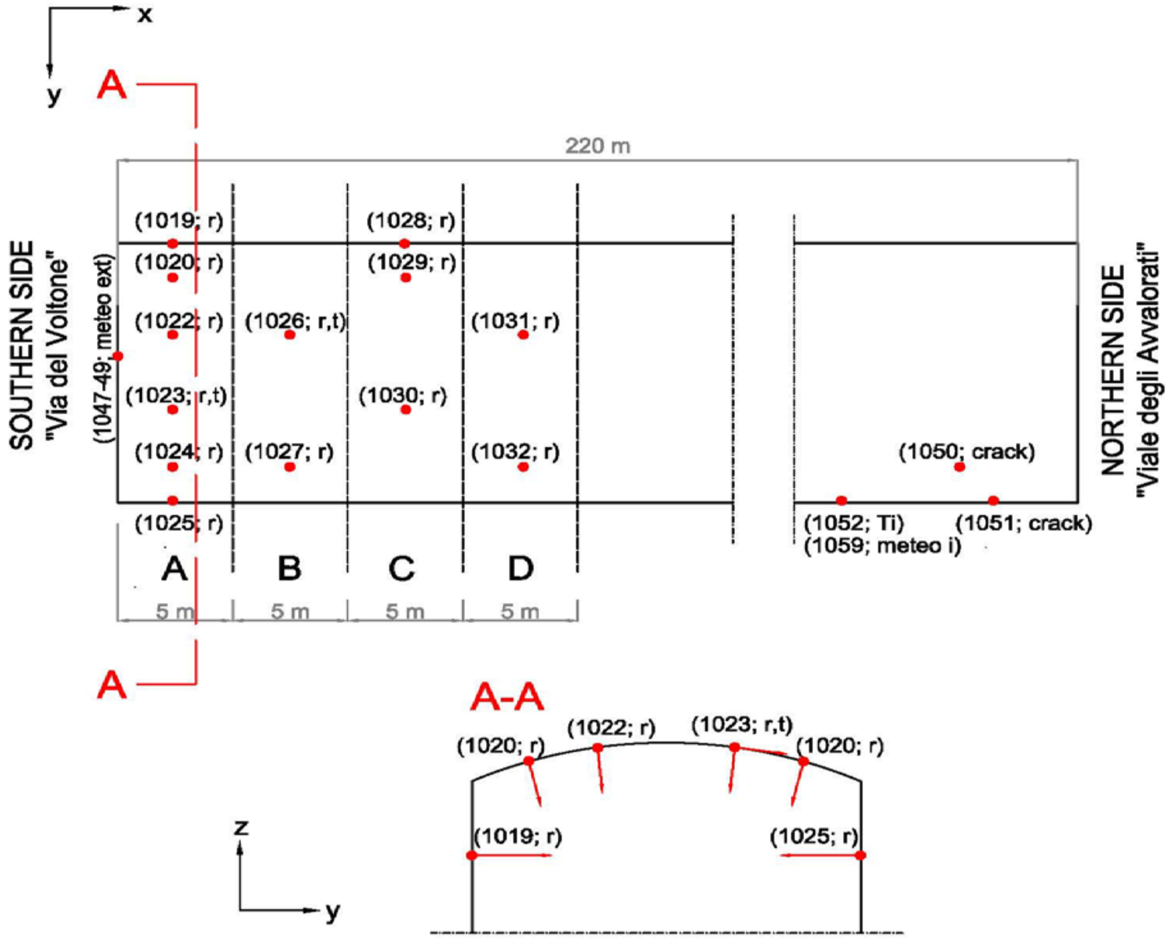


Figure 8. Long-term monitoring system: final layout of the sensors.

5. Data analysis

5.1. Acceleration data

The signals recorded by the monitoring system are herein presented and discussed. Tables 1, 2 and 3 summarise the peak values of the acceleration (a_{max}), the Root Mean Square (RMS) and the Signal to Noise Ratio (SNR) of the signals recorded in the radial direction in the period of interest. For the sake of brevity, only the records of the most representative instruments are reported in the tables.

The maximum acceleration values are in the order of 0.01 – 0.05 g**,** with the highest values recorded in the first two areas (A and B), under “Via del Voltone”. The order of magnitude of these acceleration values appears stable in the monitoring period.

The values of the SNR ratios shown in Table 3 are in good agreement with the minimum levels recommended in the literature for the dynamic identification of large civil structures via ambient vibrations. The SNR ratios allow a first assessment of the signal quality in operational modal analysis. The American standards ANSI S2.47 (1990) recommend a minimum level of 5 dB and propose some corrections in the range 5–10 dB, while (Brincker and Ventura, 2015) suggest a minimum level of 30–40 dB, which corresponds to the values shown in Table 3.

Figure 9 and Figure 10 show the RMS (maxima over the day) of the signals recorded in the areas from A to D. In particular, Figure 9 shows the values recorded in the tunnel’s lateral walls, while Figure 10 those recorded in the vault.

The order of magnitude of the RMS values is stable during the monitoring period.

The energy content of the signals recorded in the vault turns out to be higher than that recorded in the lateral walls. Moreover, Figure 10 highlights the different energy content of the signals in the four areas of the vault: it is maximum in the first two areas (A and B), located under “Via del Voltone”, and tends to decrease going inward in the tunnel (D area), which is located under the pedestrian square. These observations allow to identify the traffic on the square as the primary vibration source for the monitored structure.

Table 1. Peak values of the acceleration [g] recorded in radial direction by the MOSCARDO accelerometers from November 2018 to November 2019.

	Zone A		**Zone B**	**Zone C**		**Zone D**
Sensor	**1022**	**1025**	**1027**	**1028**	**1029**	**1032**
11/2018	0.06714	0.00404	0.02545	0.00632	0.01243	0.00329
12/2018	0.01357	0.00698	0.01008	0.01937	0.01271	0.00755
01/2019	0.05945	0.01737	0.04203	0.01911	0.01944	0.01304
02/2019	0.03365	0.00612	0.00882	0.01933	0.02012	0.00360
03/2019	0.01424	0.00436	0.00839	0.01936	0.01970	0.00815
04/2019	0.01754	0.00615	0.00720	0.01954	0.00731	0.00644
05/2019	0.01469	0.00879	0.00779	0.01953	0.00648	0.00551
06/2019	--	--	--	--	--	--
07/2019	0.01398	0.01161	0.01734	0.01990	0.01624	0.00839
08/2019	0.05990	0.01249	0.01603	0.02194	0.01663	0.02867
09/2019	0.02304	0.00633	0.01837	0.02279	0.01553	0.03855
10/2019	0.03642	0.00379	0.01183	0.01936	0.01472	0.00572
11/2019	0.00948	0.00705	0.01894	0.02028	0.01842	0.03289

Table 2. Peak values of the Root Mean Square [g] recorded in radial direction by the MOSCARDO accelerometers from November 2018 to November 2019.

	Zone A		**Zone B**	**Zone C**		**Zone D**
Sensor	**1022**	**1025**	**1027**	**1028**	**1029**	**1032**
11/2018	0.0053	0.0011	0.0044	0.0012	0.0021	0.0029
12/2018	0.0038	0.0008	0.0047	0.0009	0.0039	0.0020
01/2019	0.0033	0.0007	0.0031	0.0008	0.0018	0.0027
02/2019	0.0033	0.0007	0.0035	0.0008	0.0017	0.0020
03/2019	0.0051	0.0007	0.0037	0.0009	0.0024	0.0023
04/2019	0.0041	0.0007	0.0054	0.0010	0.0032	0.0035
05/2019	0.0054	0.0007	0.0050	0.0010	0.0034	0.0050
06/2019	--	--	--	--	--	--
07/2019	0.0066	0.0007	0.0055	0.0011	0.0056	0.0059
08/2019	0.0095	0.0008	0.0074	0.0011	0.007	0.0078
09/2019	0.0081	0.0007	0.0069	0.0010	0.0056	0.0056
10/2019	0.0052	0.0007	0.0046	0.0009	0.0031	0.0044
11/2019	0.0127	0.0007	0.0092	0.0011	0.0108	0.0105

Table 3. Peak values of the Signal to Noise Ratio [dB] recorded in radial direction by the MOSCARDO accelerometers from November 2018 to November 2019**.**

	Zone A		**Zone B**	**Zone C**		**Zone D**
Sensor	**1022**	**1025**	**1027**	**1028**	**1029**	**1032**
11/2018	47.94	29.11	36.88	29.83	33.77	26.91
12/2018	44.63	21.12	35.93	23.62	33.50	25.88
01/2019	41.09	20.40	33.06	21.87	29.88	25.64
02/2019	42.87	20.12	34.01	22.57	30.12	25.41
03/2019	45.35	20.46	35.01	23.19	32.32	26.06
04/2019	44.38	20.52	35.19	23.94	31.97	26.38
05/2019	46.85	20.49	34.97	24.02	32.52	27.58
06/2019	--	--	--	--	--	--
07/2019	45.24	20.93	34.59	24.90	35.15	26.06
08/2019	47.98	21.04	36.31	25.17	36.37	29.98
09/2019	46.64	20.25	35.62	24.05	34.65	25.40
10/2019	45.09	19.82	34.32	23.05	31.99	25.52
11/2019	43.36	19.93	35.66	24.37	35.17	28.44

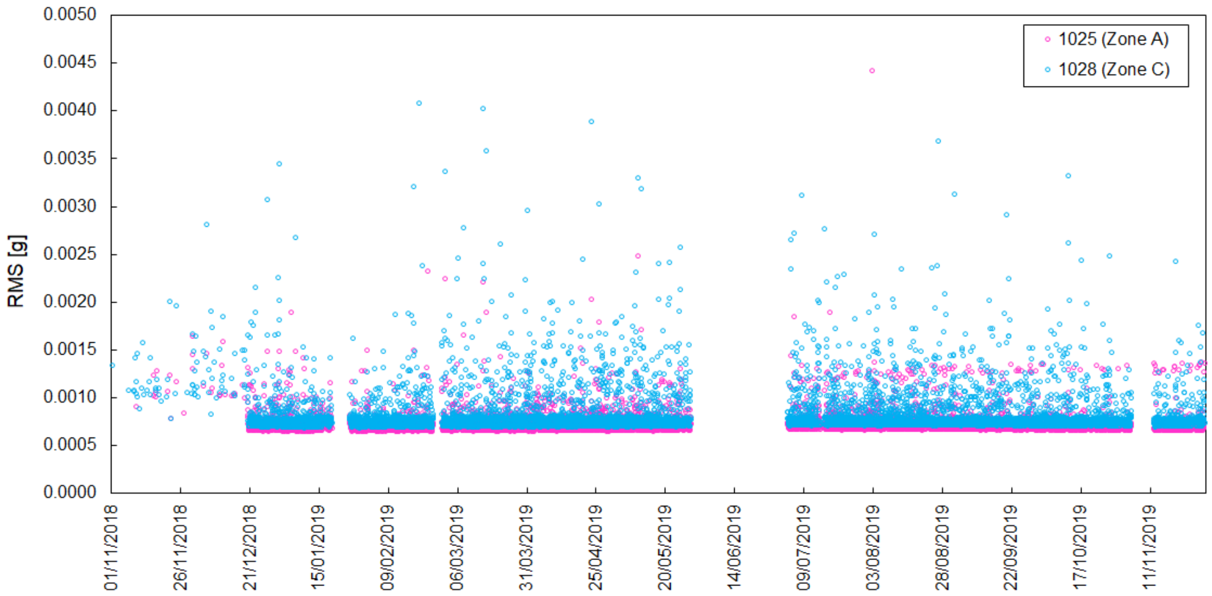


Figure 9. RMS of the signals recorded by the MOSCARDO accelerometers placed on lateral walls from 1 November 2018 to 30 November 2019.

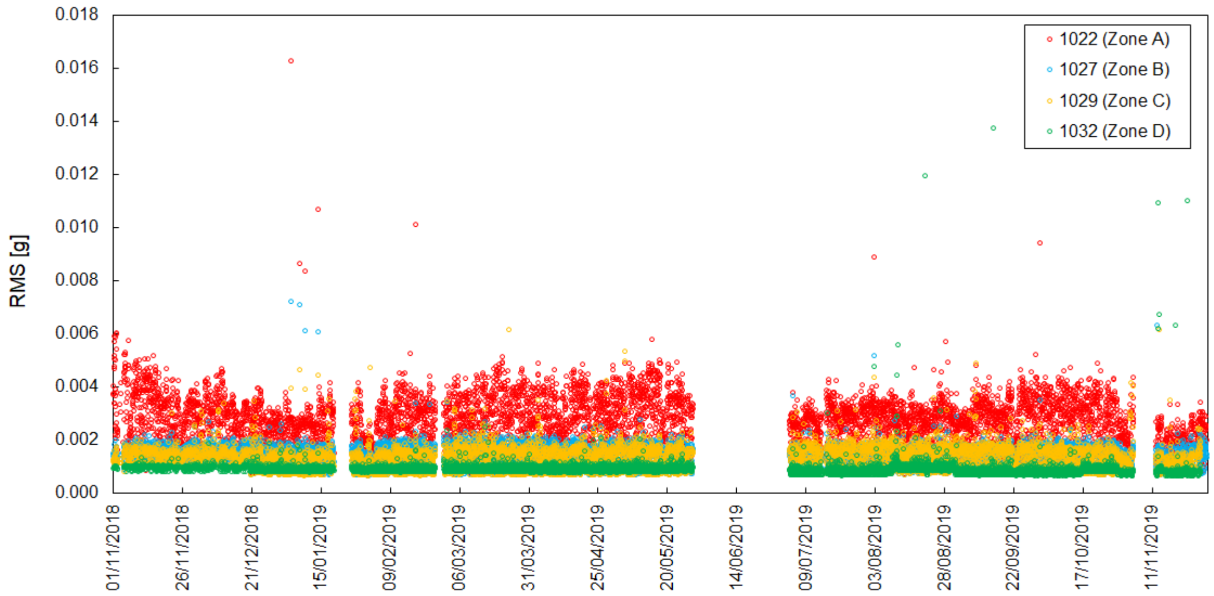


Figure 10. RMS of the signals recorded by the MOSCARDO accelerometers placed on the vault from 1 November 2018 to 30 November 2019

5.2. Crack monitoring

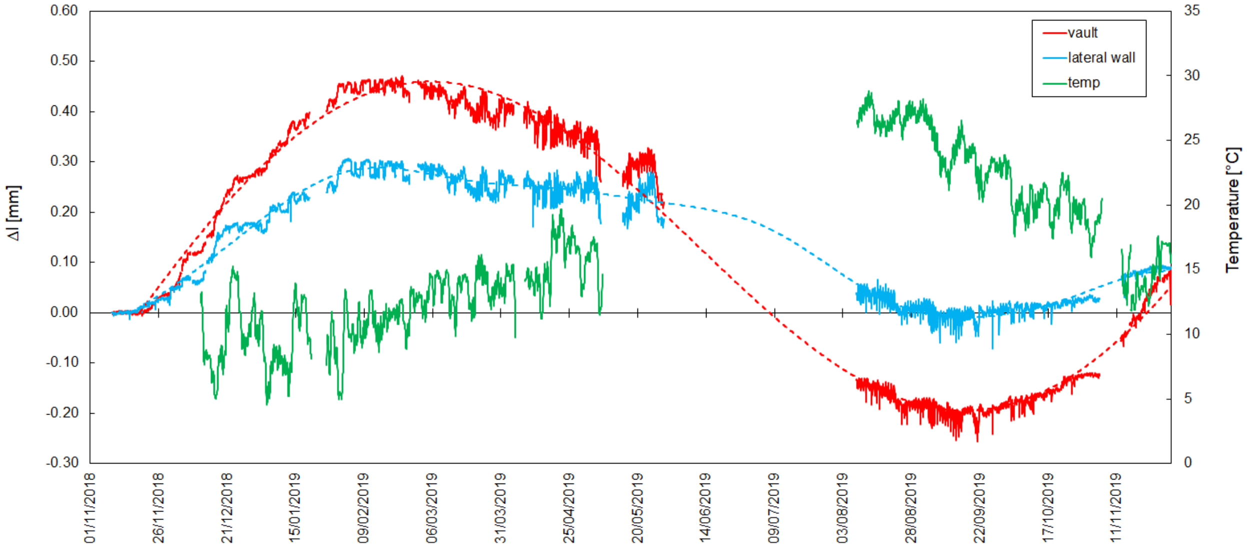
The “Voltone” is located in an environment with very high humidity levels. The effects of these adverse environmental conditions are well visible in the stone coverings of the facades and the material surfaces of the tunnel. The masonry structure appears, however, in fair maintenance conditions. The only visible crack inside the tunnel is in the northern part of the structure: the crack involves the eastern wall and a portion of the vault (see Figure 11). Two linear displacement transducers (indicated as 1050-1051) were installed on the crack, together with a sensor for temperature and humidity measurements.

Figure 12 shows the elongation of the cracks in the vault and wall, together with the values of temperature and humidity measured nearby the cracks. The measurements are shown over the whole monitoring period (about one year). They exhibit a sinusoidal trend over the year, which has been highlighted in the figures. The correlation of crack lenghts with temperature is moreover evident, while the values of the relative air humidity in the tunnel are almost constant during the monitoring period and seem not to influence the opening/closing of the cracks. The absence of significant long-term trends in the measured elongations denotes that the cracking phenomenon is mostly stable.

(a)

(b)

Figure 11. Crack in the eastern wall (a) and installation of the displacement transducer (b).



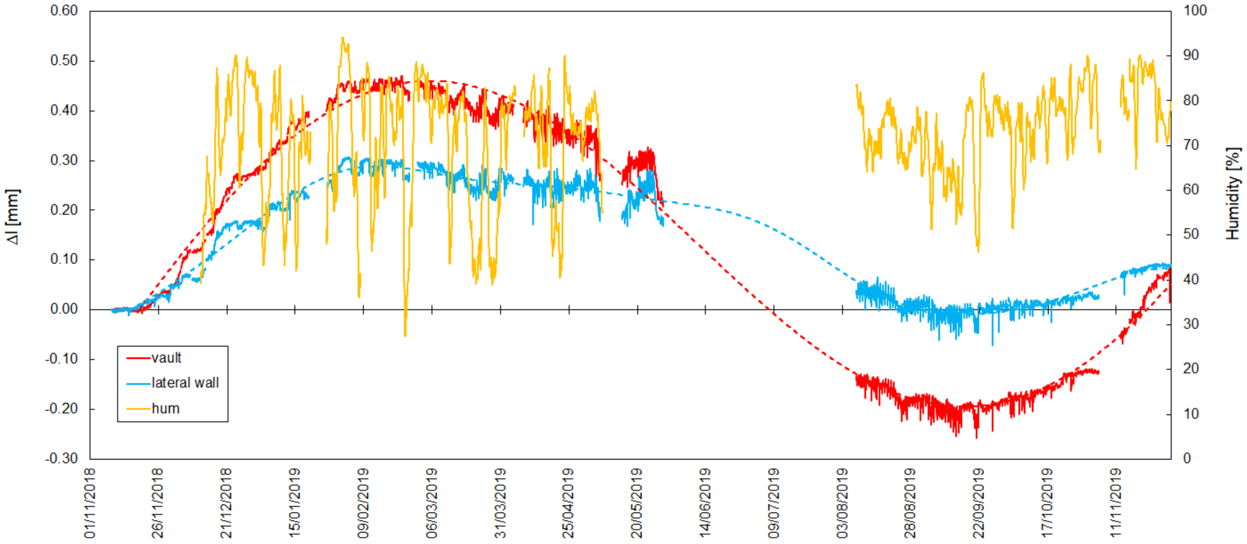


Figure 12. Elongation of the crack on the vault (transducer 1050, red line), on the lateral wall (transducer 1051, blue line), temperature (transducer 1052, green line) and humidity (transducer 1059, yellow line) from 1 November 2018 to 30 November 2019.

6. Conclusions

The paper reported the results obtained in the framework of the MOSCARDO project and focused on the dynamic monitoring of the “Voltone”, a tunnel-like masonry structure located under Piazza della Repubblica in Livorno. A wireless sensor network was installed on the structure in November 2018 and connected to a remote server, where data were collected and processed. The WSN monitoring system ran until December 2019, following the work plan of the project. The experiment was challenging, both for the type of structure involved and for the difficulty of installing the monitoring system. To the best of authors’ knowledge, no similar experiences are reported in the literature. The monitoring system proved to be able to catch and follow during the time the main features of the dynamic behaviour of the tunnel. In particular, its response to the action of vehicular traffic on the overlying square seems not to present critical issues..

Acknowledgements

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