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Implementation of a seismic monitoring network of relevant and strategic public buildings in the Marche region (Italy)

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ABSTRACT

A seismic monitoring infrastructure for relevant and strategic public buildings has been developed thanks to the agreement between the National Institute of Geophysics and Volcanology (INGV) and Marche Region. The project was founded by European projects for the assessment of seismic risk for strategic public buildings, prevention and monitoring - European Territorial Cooperation Project Holistic (EU IPA-Adriatic) and READINESS (INTERREG Italy-Croatia). The project was born by taking advantage of the presence of MEMS accelerometers installed at the base of municipal buildings. The project aims to implement low-cost technologies and non-invasive methods to extend the seismic monitoring of the sites where the structures are located and characterize the seismic action in correspondence of them with a rapid estimate of the damage through relationships between acceleration and macroseismic intensity or fragility curves and construction features. Among the various activities, environmental seismic noise measurements were carried to investigate the fundamental vibration of the structures and soils, semi-automatic procedures were developed for the calculation of the strong motion parameters of seismic events and a web portal was implemented for the collection and rapid dissemination of information to local Civil Protection.

An important part of the activities concerned the testing of new MEMS accelerometers through collaboration with the Polytechnic University of Marche (UNIVPM) and the headquarter of the Osservatorio Nazionale Terremoti (ONT) in Palermo. Moreover, new monitoring sites are being prepared in some municipalities affected by the 2016 seismic sequence. Since the beginning of the project, the strong motion parameters relating to 95 seismic events of magnitude greater than 3 and with ground motion accelerations greater than or equal to 0.001 g have been stored in the database.

KEY WORDS: urban seismic networks, structural monitoring, MEMS, seismic sensor

INTRODUCTION

The idea of seismic monitoring of public buildings was developed in the framework of the European projects Holistic (Adriatic IPA Cross-border Cooperation Program) and READINESS (INTERREG Italy-Croatia) and realized by the collaboration between the Ancona branch of National Institute of Geophysics and Volcanology (INGV) and the Functional Centre of the Integrated Security Policies and Civil Protection Department - Marche Region (DPISPC).

In the first part of the activities, in the pilot project, some strategic public buildings were instrumented at the base with low-cost accelerometer (Ladina et al., 2015). The main idea was to implementing a network for monitoring the sites where structures that house a permanent seismic station are located and creating a dedicated database.

For permanent instrumentation it was proposed to use the accelerometer installed at the base of the buildings to detect ground accelerations during significant seismic events.

For this reason the actions of implementation are test of new low cost sensors, development of procedures with low cost instrumentation and non-invasive measures, installation of new accelerometric stations, automation of the processing of the shaking parameters, involvement of local administrations hosting the monitored sites. The inherited product is a monitoring infrastructure dedicated to the measurements of the seismic ground motion in correspondence of relevant and strategic public buildings (SPB) and the future integration of the existing infrastructure with newly developed technologies.

The hope is that existing technologies and those that will be developed in the future, such as MEMS accelerometers (Micro Electro-Mechanical Systems), can be integrated, with high dynamics, high gain, reduction of instrumental noise, but maintaining a low economic cost.

The study of low cost sensors is a challenge in recent years. Monitoring could be spread over a wider range and with reduced costs so that it can also be proposed to local communities, such as public structures and municipalities and in view of being able to integrate this type of sensors in monitoring networks and within systems of early warning like Earthquake Early Warning (EEW) (Pierleoni et al., 2018).

A second activity of this project consists of three temporary high-sensitivity seismic measurements, capable of recording environmental seismic noise, and proposed to collect some vibratory characteristics of the buildings and of the surrounding soil, useful to begin to understand the dynamic behavior of the structures. The measurements were performed near the accelerometer installed at the base of the building; on the highest floor and possibly in correspondence with the measurement performed at the base; outside in a garden / green area near the building and verifying the type of geological formation thanks to the collected cartography.

MATERIALS AND METHODS

The principals activities of the project are permanent monitoring with accelerometric sensors and non-invasive measurements inside and around of the building. The INGV headquarters in Ancona has enhanced the seismic monitoring action on the regional territory, installing a series of accelerometric stations in 2 areas: San Severino Marche Mountain Community and the Province of Pesaro-Urbino. These two areas were chosen because it was possible to transmit the stations with wireless networks of the Municipalities which access the regional Wi-Fi backbone Marche-Way using radio links, with a considerable saving of resource. The accelerometric stations were largely installed at the base of the public buildings where there was an ethernet network connection.

The instrumentation was mainly installed in the town hall, in a school building and a university. Some information about the buildings is shown in Table 1.

These public buildings following a seismic event play a primary role in maintaining the functionality of communities. This type of monitoring is not exhaustive in order to know the real dynamic behavior of the structures during the seismic event, obtainable only by means of instruments installed in all parts of the building, as in accordance with the Seismic Observatory of Structures (Dolce et al., 2015).

The 19 accelerometric stations are equipped with different instrument: 11 data logger GAIA2 (Rao et al., 2010), developed and built within the laboratories of the INGV equipped with MEMS Colibrys SF3000L accelerometers; 2 GAIA2 equipped with MEMS Colibrys V1000 implemented by UNIVPM (Pierleoni et al., 2018); 2 GAIA2 equipped with Episensor FBA ES-T (http://www.kinemetrics.com); 4 Lunitek Triton equipped with MEMS LTME-90 (www.lunitek.it).

The geometry of the network is described in Fig. 1 that shows the two areas of monitoring, accelerometric stations and the different type of sensors.

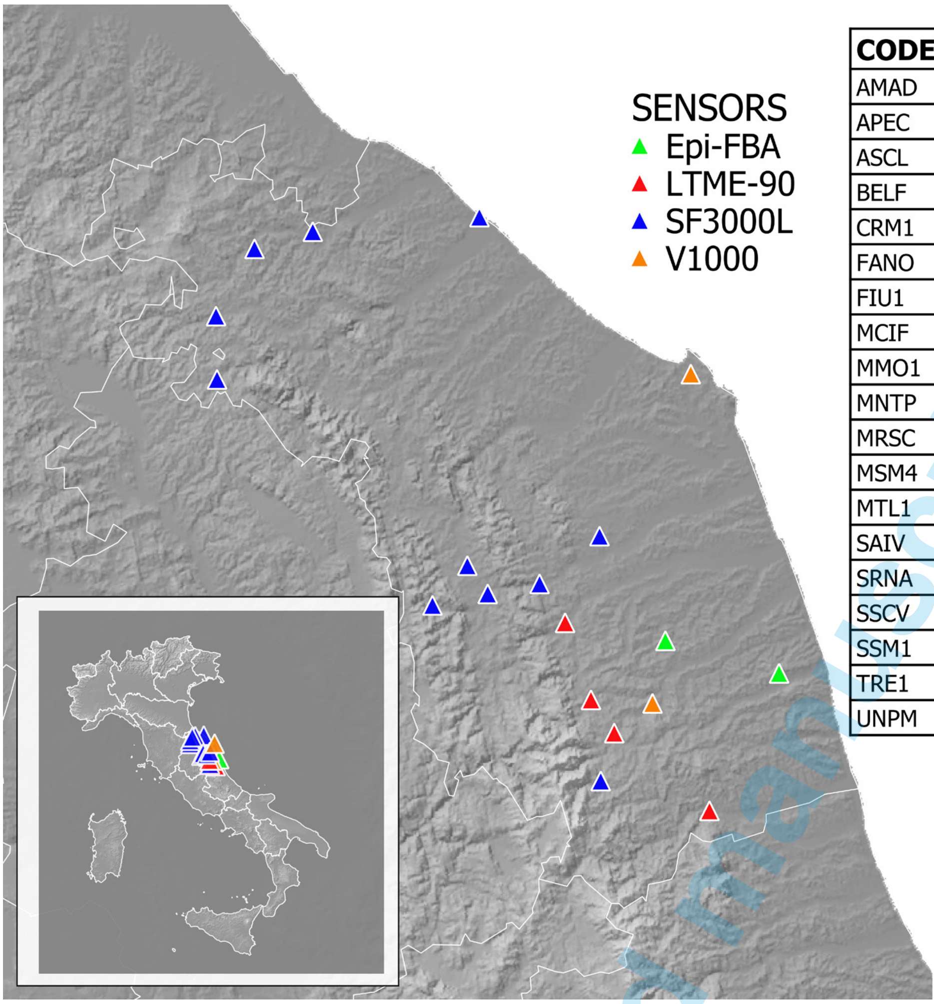
The acceleration of the soil is recorded continuously, the data is sent in real time to the INGV acquisition center in Ancona. Where possible, the accelerometric stations have been installed in the underground rooms or on the ground floor.

In the sites where the 19 SPB selected are located, environmental seismic noise measurements were carried out, useful for estimating the vibratory characteristics of the buildings and for a better interpretation of the accelerometric traces recorded by the permanent stations. The main objective of the temporary measures was to extract information from

TABLE 1

Information about buildings : Station Code (CODE), Building type (BUIL), Typology of building (TYPOL), Number of floors (N_F).

CODE	BUIL	TYPOL	N_F
AMAD	town hall	Masonry	3
APEC	town hall	Stone masonry	3
ASCL	town hall	Masonry	3
BELF	town hall	Masonry	3
CRM1	town hall	Solid bricks and lime mortar masonry	3
FANO	town hall	Reinforced concrete	4
FIU1	town hall	Partially dressed stone masonry with good bonding	2
MCIF	town hall	Partially dressed stone masonry with good bonding	2
MMO1	town hall	Stone and bricks	3
MNTP	town hall	Solid bricks and lime mortar masonry	3
MRSC	town hall	Stone and bricks	3
MSM4	school	Reinforced concrete	3
MTL1	town hall	Solid bricks and lime mortar masonry	3
SAIV	town hall	Stone masonry and bricks	4
SRNA	town hall	Masonry	3
SSCV	town hall	Reinforced concrete	2
SSM1	town hall	Stone masonry and solid bricks	4
TRE1	town hall	Solid bricks and lime mortar masonry	3
UNPM	university	Reinforced concrete	8



CODE	LAT	LON	ELE(m)	SENS
AMAD	42.980401	13.355676	501	LTME-90
APEC	43.55846	12.41991	488	SF3000L
ASCL	42.852597	13.57707	157	LTME-90
BELF	43.164276	13.237667	347	LTME-90
CRM1	43.210082	13.058016	302	SF3000L
FANO	43.843471	13.018354	15	SF3000L
FIU1	43.188571	12.931604	465	SF3000L
MCIF	43.811583	12.631683	330	SF3000L
MMO1	42.899333	13.326833	957	SF3000L
MNTP	43.137378	13.469252	325	Epi-FBA
MRSC	43.08574	13.7318	395	Epi-FBA
MSM4	43.031613	13.442229	530	V1000
MTL1	43.256732	13.009601	353	SF3000L
SAIV	43.66482	12.413039	360	SF3000L
SRNA	43.035667	13.300756	519	LTME-90
SSCV	43.779803	12.497462	331	SF3000L
SSM1	43.228783	13.176956	240	SF3000L
TRE1	43.311198	13.312848	330	SF3000L
UNPM	43.586763	13.516745	150	V1000

Fig. 1 - Map of the stations at the base of the SPB (triangles). Triangle color: type of sensors. Table: CODE) station code; LAT) latitude; LON) longitude; ELE) elevation in meter; SENS) type of sensors.

environmental seismic noise relating to the fundamental vibration modes of the building. For this reason, at least one measurement was carried out at the highest accessible floor of the building when it was not possible on the top floor; the main vibration frequencies emerge from the seismic noise signal, which are very evident on the horizontal components of the motion. In general, accelerometric stations are not able to detect the complete characteristics of the environmental seismic noise; therefore, temporary seismic noise measurements were also carried out near the permanent sensor. Another objective of the measurement campaign was to identify possible soil-structure interactions. During an earthquakes, the shaking of the soil could be changed in amplitude, frequency and direction depending on the characteristics of the soil, resulting in a site effect. To add information of the vulnerability of buildings, it is useful to estimate if the vibration of the ground, especially as regards frequency and duration, could create a soil-building resonance phenomenon. To this purpose noise signals were acquired from sensors placed on the surrounding ground outside the structures. Then, all temporary environmental seismic noise measurements were analyzed using a program with a graphics interface that allow to view and select the signal windows simultaneously with the spectral forms related to Power Spectral Density (PSD) and Horizontal to Vertical Spectral Ratio (HVSR), as described in Marzorati (2010), to exclude the noisiest windows, where transients due to anthropogenic activity are present.

The surveys for the monitoring of buildings were integrated and completed with geological characterization of the seismic stations through digital thematic cartography and morphological characteristics and the use of Geographical Information Systems techniques.

All the collected information allowed to propose a classification in the various categories of site according to Eurocode 8 [ENV-98, 2002; OPCM, 2003; NTC 2018] for the subsoil categories and the topographical conditions. The vector geological cartography available is on a scale of 1: 10,000 (Ladina et al., 2015). For the characterization, the geological surface formations are classified by lithological characteristic to insert in the velocity class of EC8 code. The classified geological layer was crossed with seismic stations layer to assign EC8 soil class to the site. Regarding the morphological classification of the sites, the slopes and the presence of topographic crests near the stations were extracted from the TINITALY/01 DEM at 10 meters resolution with methods for hydrogeology following the scheme described in (Pessina and Fiorini, 2014). The values of slope and presence of ridges have been used to assign EC8 topographic category to the sites.

The continuous seismic data recorded by the accelerometers in SPB are transmitted in real time and processed in Ancona INGV-ONT headquarter (Cattaneo et al., 2017). For the analysis of this data a time window containing the earthquake waveform is extracted, the start is 10 seconds before P arrival and the length is the double time of significant duration D, calculated from 5% to 95% of the Arias Intensity (Cauzzi et al., 2016). The seismic data, available after the identification of the seismic event, are pre-processed with the following operations: Butterworth band-pass filter between 0.2-20 Hz, detrend and baseline correction, 10% cosine tapering and conversion with the sensitivity of the instrument.

The time series extracted is processed to calculate strong motion engineering parameters at each station that recorded a local magnitude ≥ 3.0 and a PGA≥ 0. 981 cm/s^2 (1 mg) (arbitrary threshold). The procedures process the seismic waveform and return the following strong motion parameters: Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Arias Intensity (AI), Housner Intensity (IH), Response Spectra at period 0.1, 0.3, 1 and 3 seconds. The results are useful to apply a preliminary damage estimation based on empirical relationships: the simplest is an estimate of the macroseismic intensity by an empirical relationship (Faenza and Michelini, 2010). An alternative is the use of specific fragility curves supplied by literature (Rota et al., 2008) or obtained by Finite Element Models (FEM), if available, to obtain more reliable estimate (D'Alessandro et al., 2019). The results collected with temporary measures and strong-motion analyzed are stored in a relational database. The automatic data analyzes are carried out over a window starting from 10 sec of phase P for a total length of 25 sec. A review is then carried out by an operator to integrate and correct the data if needed. The data are loaded into a relational database that allows to combine, through tables, the values of the strong-motion parameters obtained with the relative event and the information of the stations. Data are available in 30-45 minutes once the procedures are done.

RESULTS AND DISCUSSION

The results obtained by this project are the collection of information relating to the recordings of permanent stations inside buildings and results of temporary environmental seismic noise measurements, field tests and comparison between different sensors.

The first seismic event in the archive occurred in December 2013 and the database includes 95 seismic events until September 2019. The information and related results are collected in a website called MOSTspb (http://www.an.ingv.it/MOST), currently available only to regional Civil Protection officials. The extent of the events is between 3.0 (chosen as the lowest threshold) and the Mw 6.5, 30 October 2016, 06:40:17 UTC earthquake recorded during the 2016-2017 seismic sequence of central Italy. The epicentral distances range from 6.3 km to 157.6 km and the hypocentral distances range from 10.6 km and 157.9 km.

Many of the earthquakes belong to the 2016-2017 seismic sequence in central Italy. During the sequence the analysis threshold was raised to magnitude 4.0. In the database, the largest Peak Ground Acceleration (PGA) is 178.5 cm /s^2 recorded during the main seismic event of the sequence at 21.7 km of hypocentral distance. Always during the main event of the sequence, up to about 60 km of epicentral distance, accelerations were estimated that could have produced macroseismic intensity of VI-VII degrees, see example in Fig. 2.

The information relating to the events are useful to perform a rapid estimation of the degree of damage to the structures that civil protection can use to organize and regulate first interventions. Fig. 2 shows the municipalities and the macroseismic intensities associated below the mainshock of 30 October 2016. A simple way to assign intensity is to convert strong-motion parameters through an empirical relationship (Faenza and Michelini, 2010). Therefore, the system quickly allow to highlight municipalities that probably have been strongly affected.

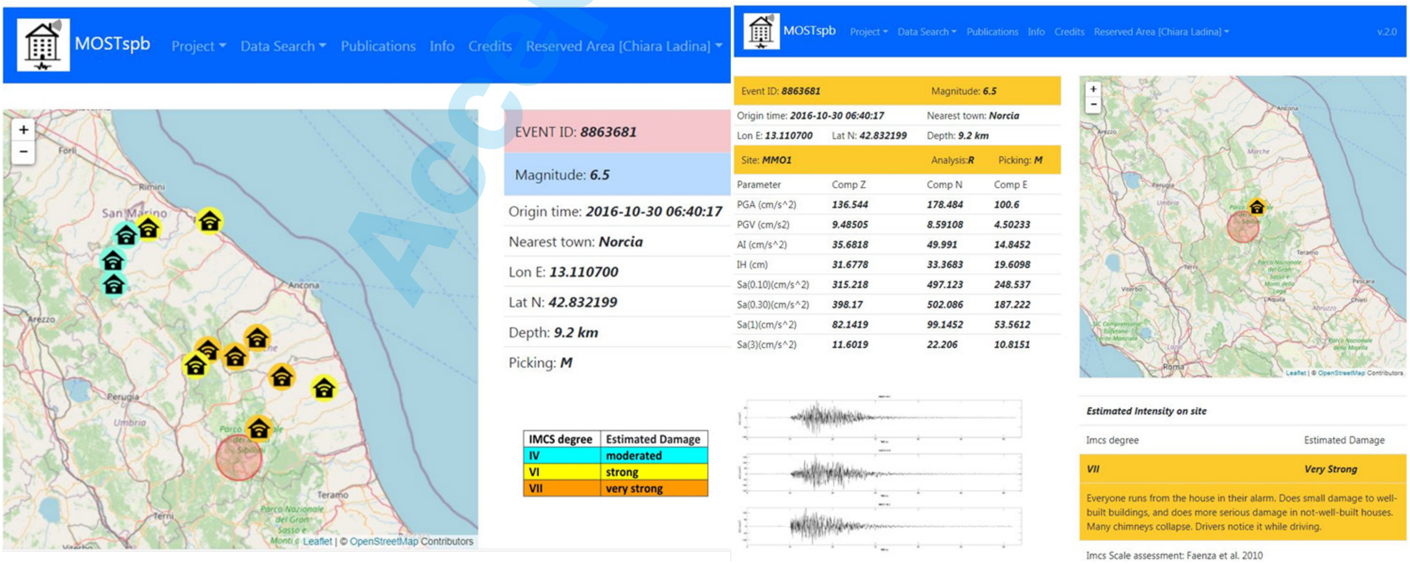


Fig. 2 - Website MOST. Left:clickable site map of earthquake recorded during the 2016-2017 seismic sequence of central Italy (Mw 6.5, 30 October 2016, 06:40:17 UTC) and view of the preliminary damage estimate (site color scale). Right: example of event-station panel and strong motion parameters recorded at a single station. The color scale represents macroseismic intensity Imcs estimated by Faenza and Michelini (2010).

In the web site it is also possible to view the results of the HVSR measurements carried out for each station on a webpage dedicated to site information. On this page the reader will find station code and coordinates, geological information, morphological information (slope, class EC8) and seismic information and a document with the details of the measurements. All this information could be useful to interpret strong-motion waveforms recorded at the sites. Fig. 3 shows an example of the results of the HVSR analysis carried out for the earthquake of 30 October 2016, Mw 6.5, recorded at the station of the municipality of Montappone (FM) compared with the temporary environmental noise measurements performed inside and outside the structure.

In the upper panel of Fig. 3, the waveform of the EAST-WEST component recorded on the base of the structure is plotted. In the lower panels of the figure, HVSR of the earthquake (left), of the noise recorded on the second floor of the building (middle) and of the noise recorded on soil outside the building (right) are plotted. The rotation of the components was performed to calculate the HVSR ratios for each direction between 0 and 175 degrees (green lines in Fig. 3).

HVSR of the earthquake was calculated on a 5 s window from S arrival and shows a clear amplification peak at 4.8 Hz with a maximum in the direction 60°N (blue line). The frequency of the peak is near at those recorded on the second floor of the building (4.09 Hz, 70° N) and on the soil (4.03 Hz, 100° N). This type of data are informative about a possible interaction soil-structure and they can reveal an increase of the seismic risk of the structure if the frequencies are similar. Then, the reports of the environmental noise measurements available on the MOST site about the seismic response of the building and the soil and the results of the analysis of the seismic events can combined with information about the vulnerability of the structure.

Then, in the second type of activities it was possible to carry out some tests by comparing low-cost sensors with reference accelerometric sensors. An example is the measurements performed during the seismic emergency of central Italy in the 2016-2017 period. Two sensors were compared directly in the field. The reference sensor was an EPISENSOR FBA EST while the TEST sensor was a Colibrys VS1002 sensor. This test was carried out in order to better study the performance of low-cost sensors especially in the recording of earthquakes at different distances and magnitudes (Pierleoni et al., 2018); in this particular test events from magnitude 2.5 to 6.5 during the seismic sequence were recorded.

CONCLUSION

The described activity concerns a project that uses different technologies in order to obtain and characterize the seismic action in correspondence of the SPB buildings and organize the relative information.

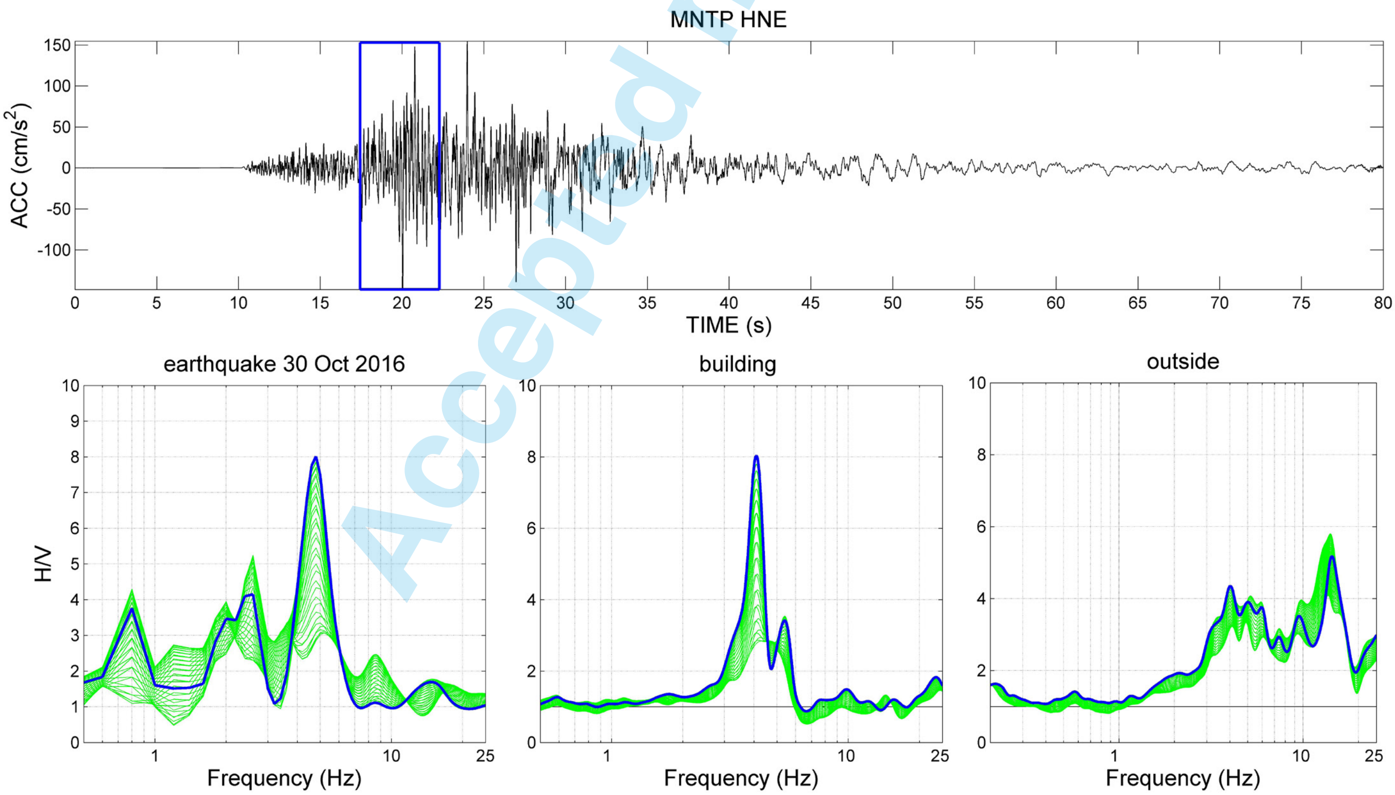


Fig. 3 - Top panel: waveform of the EAST-WEST component of the station MNTP recorded at the base of the structure. Blue box: 5 s window from S arrival used for HVSR. Bottom panels: left) HVSR of the earthquake; middle) HVSR of the noise recorded on the second floor of the building; right) HVSR of the noise recorded on soil outside the building. Green lines: Average HVSR related to the directions from 0° to 175° with an interval on 5°. Blue lines: HVSR of the maximum amplitude direction, between 1-10 Hz.

The approach used so far has been to obtain the best possible knowledge of the sites with the few resources available. This indirect approach differs from the massive monitoring of the building, involving the use of enormous economic and non-economic resources, which do not allow a wide diffusion on the territory.

The Ancona office manages 19 accelerometric stations installed inside public buildings and allows to process the seismic signal in real time and to return strong-motion parameters, for example the peak parameters like PGA recorded in each seismic station.

The data analyzed regarding the selected seismic events are stored in a database useful for reconstructing the instrumental seismic history of the structure and can be consulted on the MOSTspb website. The result is a dedicated monitoring infrastructure with accelerometers installed at the base of the buildings, data acquisition in real time, dissemination of information and useful data for assessing the seismic risk of relevant and strategic public buildings.

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