ANNALS OF GEOPHYSICS, 59, FAST TRACK 5, 2016; DOI: 10.4401/AG-7271

# Different damage observed in the villages of Pescara del Tronto and Vezzano after the M6.0 August 24, 2016 Central Italy earthquake and site effects analysis

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**Abstract**

*The authors have surveyed many damaged villages located at the epicentre of the ML=6.0 earthquake which occurred on August 24, 2016 in central Italy. Some unexpected anomalies were discovered such as very different levels of damage in Vezzano and Pescara del Tronto villages (Arquata del Tronto Municipality, Ascoli Piceno province). The two villages are situated just 1300 meters from each other. Pescara del Tronto suffered very heavy damage with many masonry building collapses and 48 fatalities, while Vezzano suffered only light damage to few buildings. This paper provides a preliminar analysis from an engineering and geophysics perspective. Particularly, rapid visual surveys were carried out in the two villages in order to detect possible significant differences in the vulnerability of their building stocks and site geophysical investigations were performed to detect possible local amplification effects.*

## I. INTRODUCTION

In the aftermath of the ML=6.0 earthquake which occurred on August 24, 2016 in central Italy, the authors surveyed many damaged villages. Among them, some unexpected anomalies were found, particularly regarding the severity of damage in Vezzano as opposed to Pescara del Tronto (Arquata del Tronto Municipality, Figure 1).


**Figure 1**: *Territorial framework of studied area (administrative territory of Arquata del Tronto) with indication of the small villages of Pescara del Tronto and Vezzano.*

Despite the villages being situated just 1300 meters from each other, Pescara del Tronto suffered very heavy damage with many masonry building collapses and 48 fatalities (on 122 inhabitants, ISTAT 2011), whereas Vezzano (12 inhabitants; ISTAT 2011) suffered light damage to only a few buildings. Considering the recent seismic history of the villages, it is worth noting that for the Mw=5.0 earthquake which occurred on 19th December, 1941 (DBMI2015, http:// emidius.mi.ingv.it/CPTI15-DBMI15/), different intensities were reported in the macroseismic catalogue, particularly higher in Pescara del Tronto (VII MCS) as opposed to Vezzano (VI MCS).

Rapid visual surveys were carried out in order to detect possible significant differences in the vulnerability of the building stocks, together with site geophysical investigations aimed at detecting possible local amplification effects.

## II. Damage in the villages of Pescara del Tronto and Vezzano

The extent of damage in Pescara del Tronto is clearly visible in Figure 2-a) showing the post-earthquake condition of a portion of the village. Figure 2-b) displays a partial collapse of a masonry building pointing out the poor quality of masonry walls without any connection between wythes. In some cases, the combined effect of in plane actions and out plane actions further exacerbated by pushing wooden roofs was responsible for the collapse. Heavy damage also occurred to buildings with reinforced concrete (RC) structure. An example is reported in Figure 3-a) and b), where the heavy damage occurred to a four storey RC building in Pescara del Tronto is shown. The infill walls of the second storey totally collapsed. They were made up of two 12 cm clay hollow brick layers with an interposed layer of insulating material.

**Figure 2:** *a) Overview of Pescara del Tronto most damaged area and b) Collapse of a typical masonry building.*

**Figure 3:** *a) Reinforced concrete building in Pescara del Tronto, b) Detail of the damage to a beam-column joint.*

Some structural damage was also found in a beam-column joint displayed in Figure 3-b). Concrete spalling affected the joint panel where no hoops are visible as expected considering design rules given in the building codes then in force (Masi et al., 2013; Manfredi and Masi, 2014; Masi et al., 2014). In fact, the presence of deformed reinforcing bars indicates design and construction could date back to the early 1980's (Masi et al., 2015), when Arquata del Tronto was classified as a seismic zone, forcing engineers to consider seismic activity without particular attention to structural details. A possible interaction with a retaining wall could also be partially responsible for the undesired seismic behaviour of the building. Both severity and extent of damage in Vezzano were found to be quite different, as well as no fatalities or injuries were reported. The lack of heavy damage was confirmed during the rapid survey carried out by the authors and most of buildings appear to be undamaged (Figure 4-a), apart from a few abandoned and dilapidated buildings (Figure 4-b).

## III. Comparison between typological characteristics of building stocks in Pescara del Tronto and Vezzano.

Building stocks in Pescara del Tronto and Vezzano show typical characteristics of central Apennine villages affected by earthquakes (Mucciarelli et al., 2003; Masi et al., 2014b). The 2011 ISTAT survey (see Tab.1) reports that the building stock in both

**Figure 4:** *a) Undamaged buildings in the main square of Vezzano village and b) Partial collapse of an abandoned building.*

villages was made up mostly of low-rise masonry structures in a good state of preservation, however, designed without any reference to seismic criteria (Arquata del Tronto municipality was classified as seismic in 1983). Most buildings in Pescara del Tronto are 2-3 storey, rarely 4 storeys and have an unreinforced masonry structure. About 60% of surveyed buildings were classified as "mixed" and are mainly masonry built structures on the first floor and the remainder in reinforced concrete. Only 4 buildings in Pescara have reinforced concrete (RC) structures while in Vezzano there are not buildings in RC structure. Rapid/Initial visual surveys, carried out by authors in Pescara del Tronto, show that the quality of masonry buildings appear to be very poor with highly inhomogeneous stone elements. Irregular limestone block walls were frequently found, sometimes with brick elements or travertine stones (very soft and porous rock used mostly for aesthetic purposes, Figure 5-a), mortar quality was also checked and found to be very poor. Mortar generally appears to be made up of sand and hydraulic lime providing a very low bond between stones, mainly due to age deterioration, thus contributing to poor seismic performances. Several buildings in Pescara del Tronto had been subject to further construction adding one or two storeys. Figures 5-b and 5-c highlight a typical case of a building with a limestone basement and the upper two storeys made up of hollow clay bricks that appear inappropriate for structural purposes. Another prominent aspect related to the main structural characteristics of masonry buildings in Pescara del Tronto concerns the wall corners which are generally of poor construction quality,

**Table 1:** *Data extracted from the 2011 Italian population and housing census (ISTAT, 2011)*

| | | Pescara del Tronto | Vezzano |
|---|---|---|---|
| **Inhabitants** | | 122 | 12 |
| **Typology of dwelling buildings** | Masonry | 37 | 34 |
| | R.C. | 4 | 0 |
| | Mixed | 69 | 2 |
| **Age of Buildings** | <1919 | 88 | 32 |
| | 1919-1960 | 14 | 3 |
| | 1961-1980 | 6 | 1 |
| | >1980 | 2 | 0 |
| **Number of Floors** | ≤2 | 47 | 12 |
| | 3 | 59 | 23 |
| | ≥4 | 4 | 1 |
| **State of Preservation** | Excellent | 14 | 6 |
| | Good | 65 | 24 |
| | Mediocre | 21 | 6 |
| | Very bad | 10 | 0 |

**Figure 5:** *a) Travertine blocks of a collapsed building, b) Building with two added floors made of hollow bricks, c) Detail of the hollow*

resulting in a poor collaboration between orthogonal walls. Besides, it appears that strengthening tie rods were absent, although their use cannot be excluded as they are rather difficult to detect in the case of a totally collapsed buildings. Floors were usually made of wooden or steel beams and in some cases, shallow arch vaults. In addition to the poor quality of masonry walls and the lack of connection between them, heavy reinforced concrete roofs were sometimes found. Such a combination caused the disintegration of the load bearing masonry walls and, in turn, the total collapse of the building. Masonry buildings of Vezzano have generally better quality with respect to Pescara del Tronto and wall corners with a more effective connection were frequently found (Figure 6-a). Few cases of additional storeys and heavy RC roofs were found. Strengthening tie rods were substantially absent. Masonry walls appear to be made up of limestone elements without travertine elements thus making them stronger, although global resistance is also dependent on the mortar quality which could not be checked. In a few cases, enlargement interventions can be noted as in Figure 6-b, although they rarely affect the global behaviour of the building. Better quality stone elements and corner connections between orthogonal walls, fewer additional upper storeys and heavy RC floors would suggest less vulnerability of the masonry buildings in Vezzano with respect to Pescara del Tronto.

**Figure 6:** *a) Buildings with good quality corners, b) Building with badly constructed enlargement.*

The seismic vulnerability of masonry buildings can be judged as generally high, considering vertical and horizontal structural types, and in general a seismic vulnerability class "A" and "A-B can be assigned for Pescara and Vezzano, respectively, according to the EMS 98 classification (Grunthal, 1998).

## IV. Geophysical survey of Pescara del Tronto and Vezzano

A geophysical survey was carried out with the aim of distinguishing sites where increased local damage was due to lower quality buildings and/or to local geo-structural settings responsible for ground motion amplifications (Mucciarelli et al., 2009). Electrical Resistivity Tomography (ERT), single and multi-station noise measurements (HVNSR, seismic array) and single station earthquake recordings (HVSR) were carried out in the investigated sites (Figure 7 for Pescara del Tronto and Figure 9 for Vezzano).

**ERT**. An ERT survey was performed at Pescara del Tronto using a Syscal Pro resistivity meter (Iris Instruments), coupled with a multielectrode acquisition system (48 electrodes), using a constant spacing of 'a' = 5m between the adjacent electrodes. In order to improve data quality and resolution, apparent resistivity data was acquired along with each profile through different array configurations (Wenner and Wenner–Schlumberger), and coupling measurements with different combinations of dipole length (i.e., 1a, 2a, 3a) and 'n' numbers of depth levels (overlapping data levels).

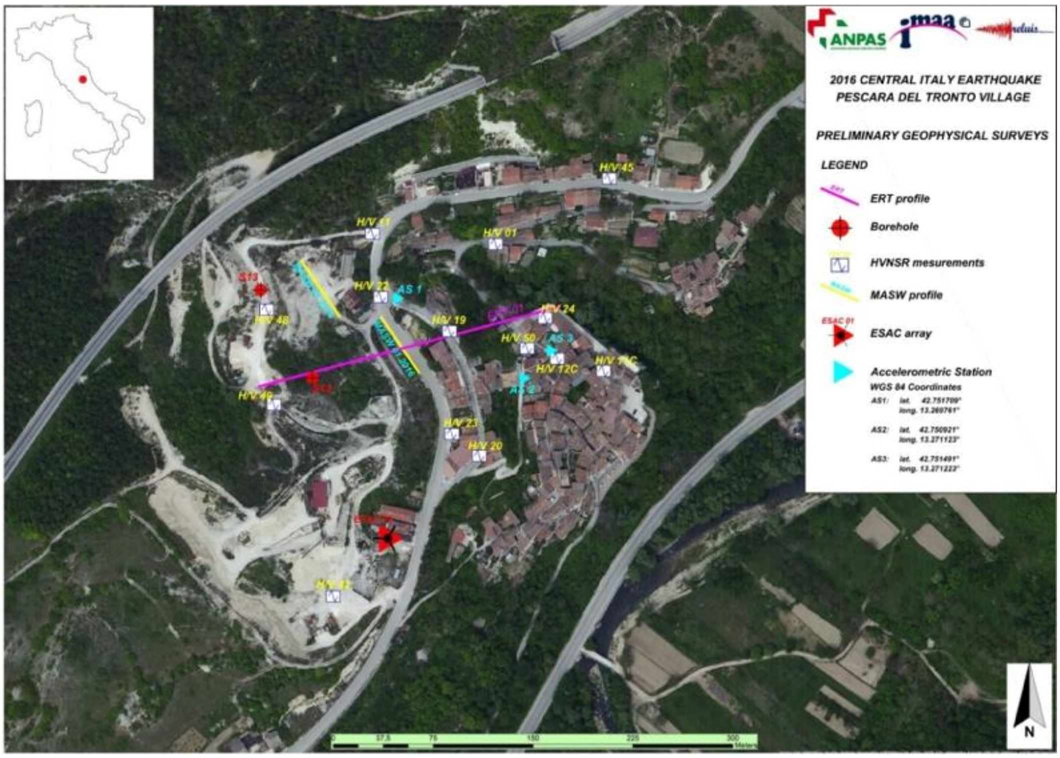


**Figure 7:** *Sketch map of the investigated area at Pescara del Tronto with location of the geophysical surveys.*

The 235 m-long ERT reached an investigation depth of about 40 m. To obtain two-dimensional resistivity images of the subsurface, the apparent resistivity data was inverted using RES2DINV software (Loke, 2001; Galli et al., 2006; Giocoli et al., 2011). The best results were obtained by means of the Wenner array, which showed a higher signal-to-noise ratio. The root mean-squared (RMS) error was 5.1% after 5 iterations (Figure 8). Overall, the electrical image shows a relatively low resistivity range, from 10 to over 320 Ωm, and a resistivity pattern characterised by relatively strong lateral and vertical gradients. The shallow relatively high resistivity layer could be attributed to slope deposits, overlying the substratum constituted by the pre-evaporitic member of the Laga Formation, according to the geological map of the area (Marche Region Geological Maps at http://www.ambiente.marche.it). In particular, the relatively conductive sectors could be related to the pelitic-arenaceous lithofacies (LAG1e), with a consistent water content, whereas the relatively resistivity sectors, especially in the center of the ERT, could be associated with the arenaceous-pelitic lithofacies (LAG1b) of the Laga Formation.

**Single station noise measurements (HVNSR)**. 14 and 3 single station noise measurements (Horizontal-to-Vertical Spectral Ratio, HVNSR, Bonnefoy-Claudet et al., 2006; EVG1-CT-2000-00026 SESAME, NATO-SfP980857) with 20 minutes of recordings sampled at 128 Hz using Tromino equipment (Moho srl) were carried out in the whole urban area of Pescara del Tronto and Vezzano, even in the most heavily damaged areas where accessibility with other instruments was problematic (Figure 7). Figure 8 shows the Pescara del Tronto HVNSR functions of the measurement points close to the ERT profile. As shown in ERT prospecting, although some sites lay on slope deposits and others are on the Laga lithofacies (LAG1e and LAG1b), all have amplification in the frequency range 3-7 Hz, that is the range of greater interest of the built-up environment (mainly low-rise masonry buildings).

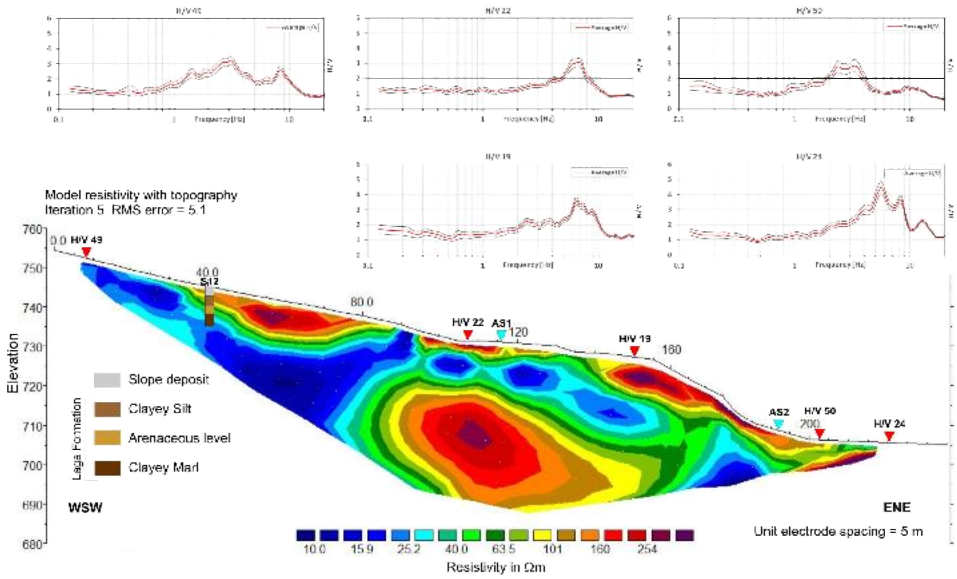


**Figure 8:** *Electrical image (ERT 01) with HVNSR functions (on the top) carried out at Pescara del Tronto.*

Although the lito-stratigraphic geological condition in Vezzano is comparable with Pescara del Tronto (Marche Region Geological Maps at http://www.ambiente. marche.it), the HVNSRs estimated in Vezzano shows flat amplitude values (Figure 9). **Seismic Array**. Mechanical characterization of shallow soil for both passive (bi-dimensional seismic arrays processed with Extended Spatial Auto-Correlation, ESAC; Ohori M., 2002; Okada 2003; Parolai et al., 2006) and active techniques (Multistation Analysis of Surface Waves, MASW; Park et al., 1999.) were applied (Figure 7). For brevity, only the ESAC survey is reported in this paper, it was performed using a Geode, a 24 bit seismometer with 144 dB dynamic range with 8 msec sampling rate. The set-up of arrays was with 24 geophones with 4.5 Hz frequency, L-shaped arrays with variable inter-distance and length in the 190 – 50 metres range were used for ESAC. Noise acquisition was carried out with a 125 msec sampling rate for a length in the range 3-40 minutes; Figure 10 reports the VS velocity profile estimated by ESAC analysis: two impendence contrasts are present at about 10m (VS from 300 to 600m/sec), probably due to the discontinuity between slope deposits and the underlying Laga Formation, and at about 30m (VS from 600 to 1000 m/sec), probably due to the different lithostratigrafic members, from pelitic to arenaceous, in the frame of the Laga Formation.

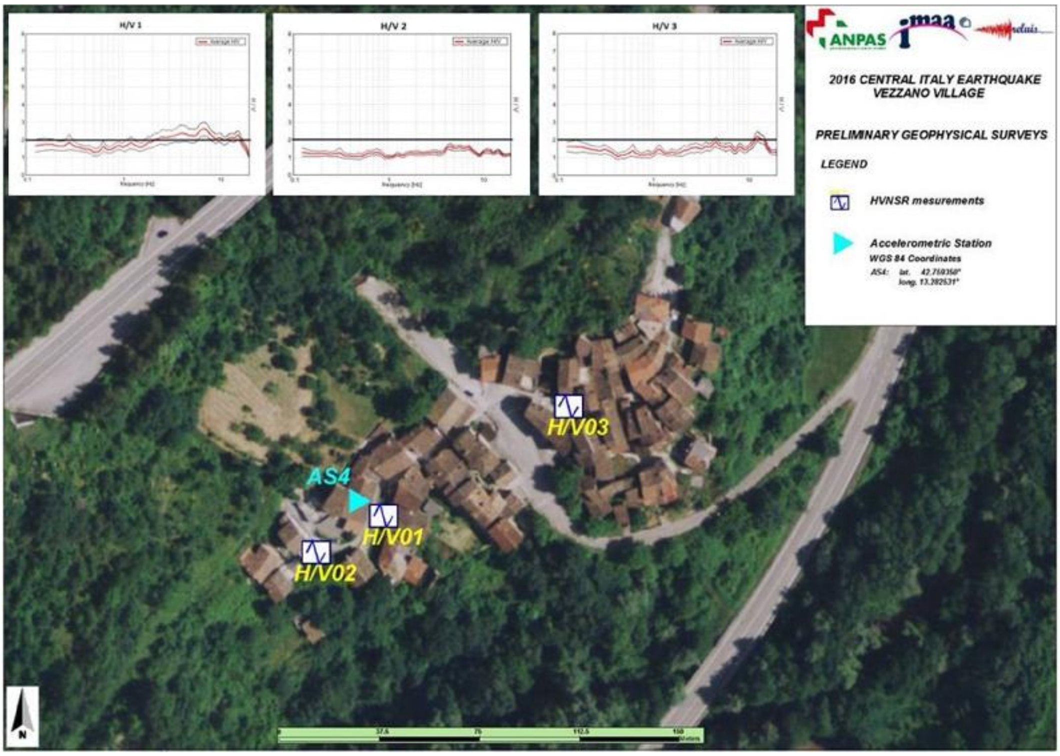


**Figure 9**: *Ambient noise HVSR functions estimated in Vezzano.*

**Single station earthquake measurements (HVSR).** To validate the site response evaluated by single station noise measurements, two ETNA-Kinemetrics accelerometers were installed on September 9, 2016 with different equipment arrangements. The aftershocks in three sites of Pescara del Tronto (AS1, AS2, AS3) and one in Vezzano (AS4) were recorded (Figure 7 for Pescara del Tronto e Figure 9 for Vezzano). Accelerometric station 1 (AS1) acquired 471 aftershocks from 7 to 10 September with magnitude in the range 1.1-4.3 ML. Accelerometric station 2 (AS2) recorded 1113 earthquakes from 8 to 27 September with magnitudes in the range of 1.1-3.9 ML, while accelerometric station 3 (AS3) was installed in the most damaged area from 28 September and is still acquiring data. Because the Vezzano HVNSRs have a flat response, an accelerometric station as a reference site was installed in Vezzano, recording earthquakes simultaneously with AS2 and AS3 stations. The preliminary Horizontal-to-Vertical Spectral Ratio (HVSR) functions were performed using 80 earthquakes with 2.4 ≤ ML ≤ 4.3 in AS1, 60 earthquakes with 1.2 ≤ ML ≤ 3.3 in AS2, 77 earthquakes with 2.2 ≤ ML ≤ 3.9 in AS3 and 88 with 2.5 ≤ ML ≤ 3.9 in the Vezzano site (Figure 11). The Vezzano HVSR estimated with earthquakes again confirms a flat amplification function, whereas Pescara del Tronto shows a significant resonance peak with a clear amplitude value (Figure 11). Although the stations are located on the same geological formation (Laga Formation), they show different amplification functions: the AS1 and AS3 sites have a clear resonance peak at about 6.5 Hz and 4 Hz respectively, whereas the AS2 site was characterised by a slight amplification in a broad frequency range (at about 2-4 Hz and 7-10 Hz, this behaviour is more evident in the WE component). It is important to emphasize that heavy damage was observed in the area close to the AS3 station.

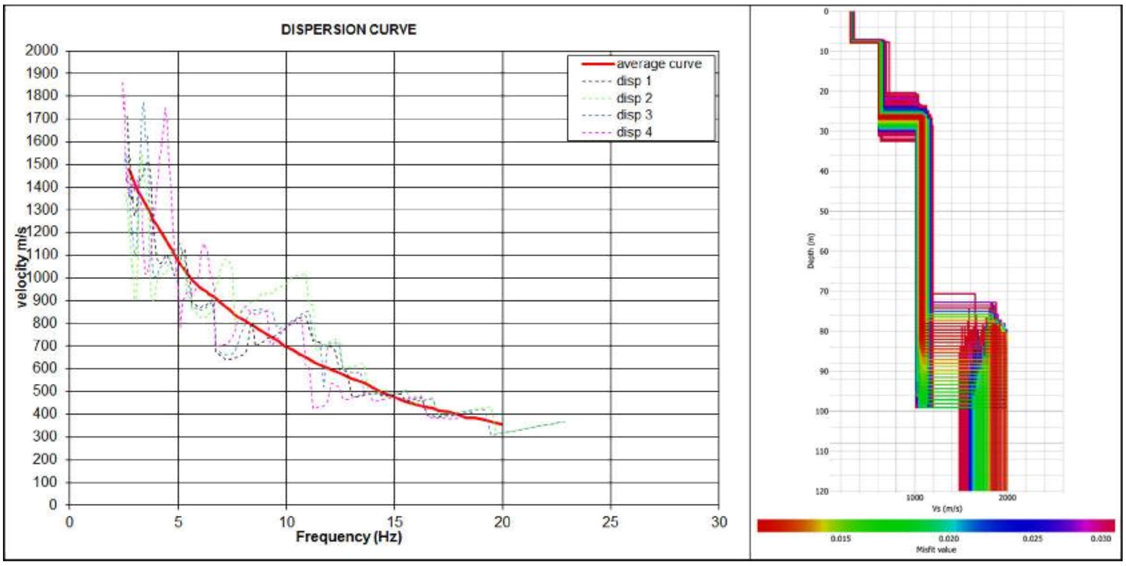


**Figure 10:**. *Dispersion curve and VS profile estimated by ESAC analysis in Pescara del Tronto.*

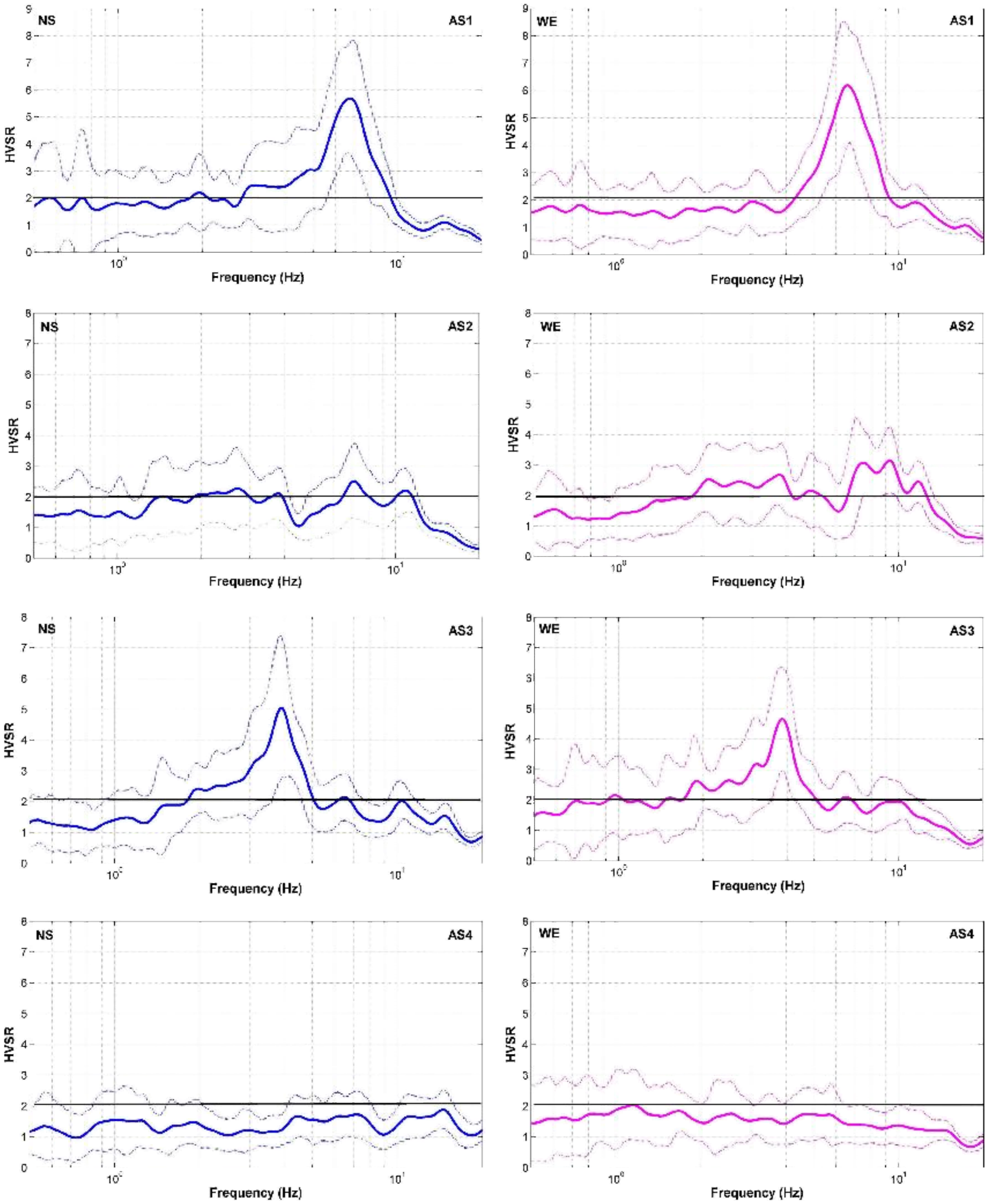


**Figure 11:** *HVSR functions estimated in three sites of Pescara del Tronto (AS1, AS2, AS3) and in one of Vezzano (AS4).*

## V. Final Remarks

Preliminary surveys of the main structural characteristics carried out on the building stocks in the Pescara del Tronto and Vezzano point out possible significant differences between the building vulnerability, although they are not so remarkable as to justify the high variability in damage distribution.

On the other hand, the results of geophysical investigations show remarkable variable local site effects determining seismic intensity amplifications in Pescara del Tronto. In particular:

1) the Vezzano HVSRs are characterised by a flat amplification function using both ambient noise and earthquake recordings;

2) the Pescara del Tronto HVSRs have a clear resonance peak at frequency between 4-6 Hz, the peak amplitude is highlighted using earthquake data rather than ambient noise recordings. Moreover the soil resonance frequency is very close to the main period of masonry buildings (~0.2 sec), this could have increased the damage in Pescara del Tronto.

Summarizing, the current status of the work allows to state that the different damage distributions in Pescara del Tronto and Vezzano are mainly due to local site effects determining seismic intensity amplifications in Pescara del Tronto, while a minor role should be attributed to the difference in terms of seismic vulnerability of buildings. However, further engineering, geological and geophysical studies are required, and currently in progress, to better understand and possibly quantify the role of the different factors (vulnerability, site effects both stratigraphic and topographic, ground settlements) on damage enhancement found in Pescara del Tronto.

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