## QUATERNARY SEDIMENTARY COVER THICKNESS VERSUS SEISMIC NOISE RESONANCE FREQUENCY IN WESTERN L'AQUILA PLAIN F. Del Monaco, F. Durante, L. Macerola, M. Tallini

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**Introduction.** The thickness of Quaternary basins sedimentary cover(hereinafter z) isone of the basic datain the evaluation of the local seismic response within the scope of urban planning purposes. One of the possible approachesto evaluate zis to determine the empirical correlation

between z and the resonance frequency (hereinafter  $f_0$ ) by means of seismic noise measurements and by using the HVNSR method (e.g., D'Amico *et al.*, 2008; Gosar and Lenart, 2010, Ibs-von Seht and Wohlenberg, 1999), by using the HVNSR method (e.g., Mucciarelli 1998; Nakamura 1989).

The z vs f<sub>o</sub>empirical equation is as follows:

$$z = a \cdot f_0^{\ b},$$

where a and b are two parameters calculated from best fitting technique (Ibs-von Seht and Wohlenberg, 1999).

**Western L'Aquila Plain geological setting.** In this paper, we report the above empirical correlation and the Quaternary sedimentary cover thickness mapping for the Western L'Aquila Plain (hereinafter WAP), struck by an earthquake on April 6, 2009 (Mw: 6.3) (e.g., Galli *et al.*, 2010; Milana *et al.*, 2011).

WAP is a typical WNW-ESE trending Quaternary basin of the central Apennines thrust and fold belt placed here in the lower Pliocene-upper Miocene times. WAP originates from Quaternary activity of the S-dipping extensional master fault of the Pettino Mt. (Galli *et al.*, 2010). Its activity produced a graben filled with Quaternary-upper Pliocene (?) clayey-sandygravelly deposits of lacustrine, fluvial and slope environments (unit C, Fig. 1) which rests on the Meso-Cenozoic carbonate bedrock (unit D, Fig. 1) (Gruppo di Lavoro MS–AQ, 2010; Tallini *et al.*, 2012). Moreover, the hill of downtown L'Aquila is characterized by 100-m thick calcareous breccia (unit B, Fig. 1) laying on the C unit as testified by deep boreholes (Del Monaco *et al.*, 2013). The unit A (Fig. 1) consists of Holocene-Upper Pleistocene alluvialcolluvial-slope deposits characterized by a gravelly-sandy-clayey lithologies, which lay upon the above-mentioned units (Del Monaco *et al.*, 2013).



Fig. 1 – Western L'Aquila Plain (WAP) simplified geological map. 1- alluvial, colluvial and slope deposits (unit A) (Holocene - Upper Pleistocene); 2- Calcareous breccia (unit B) (Middle Pleistocene); 3- fluvial and lacustrine pelite and sand (unit C) (Lower Pleistocene); 4- Meso-Cenozoic bedrock (unit D); 5- main boreholes used for z vs f0 relationship (red number refers to bedrock depth, blue abbreviation refers to borehole in Fig. 1); 6- seismic reflection profile in Tallini *et al.* (2012).

**Results.** Boreholes data and Vs values. Following L'Aquila earthquake, within the scope of buildingsreconstruction and seismic microzonation, many boreholes, among which several ones encountered the geological bedrock, and in-hole Vs tests (cross hole, down-hole and seismic dilatometer tests) were carried out in the more damaged area of WAP (Fig. 1) (Del Monaco *et al.*, 2013; GEMINA, 1963; Gruppo di Lavoro MS–AQ, 2010). These huge quantity of boreholes, along with others previously executed in the same area and geophysical investigations (seismic reflection profiles or geo-resistivity surveying), were used to constrain the z vs  $f_0$  correlation.

The Vs values were calculated from borehole tests (Fig. 3) (Del Monaco *et al.*, 2013; Di Giulio *et al.*, 2014; Gaudiosi *et al.*, 2013). The Vs value of unit D comes from a single SDMT test (pers. comm. G. Totani). The Vp values are calculated from Vs values with a Poisson's modulus of 0.35. Density and Qp and Qs, which are the estimated attenuation quality factor of Vp and Vs respectively, are estimated from literature (Gruppo di Lavoro MS–AQ, 2010).

Seismic noise measurements. The  $f_0$  spatial distribution in the studied area has been obtained through seismic noise single station measurements and the application of HVNSR method. The measuring sites were located on an irregular grid with a step of about 100-250 m. About 50 HVNSR measurements were acquired with the Lennartz MARSlite instrumentation with the sensor Lennartz 3D/5s and about 740 ones with Tromino instrumentation (Micromed S.p.A).

The sampling frequency was of 250 Hz for the Lennartz MARSlite and 256 Hz for the Tromino instrument. The acquisition time lapse was about 30-45 minutes. The two different instrumentations showed the same results for resonance frequency greater than 1-1.5 Hz (Lanzo *et al.*, 2011).

The acquired seismic noise data were analysed in the 0.1-20 Hz range with the softwares Geopsy (http://www.geopsy.org) and Grilla (Micromed S.p.A) for the Lennartz MARSlite and the Tromino instrument, respectively. Horizontal to Vertical ratio (H/V) curves were obtained by averaging the spectral ratios calculated from non-overlapping windows of 30 s. The spectra of each window were smoothed with a Konno and Ohmachi (1998) smoothing function with a bandwidth coefficient b = 40, and the HVNSR was computed at each frequency and for each window. The quality of HVNSR results were checked by using the criteria of SESAME (2004) to validate the statistical significance of the spectral ratio peaks.

The resonance frequency contouring wereplotted by using the Natural Neighbor method. The resonance frequency  $(f_0)$  ranges from 0.5 to approximately 15 Hz. The  $f_0$  lowest values (about 0.5-2 Hz) are located along the WAP central axis (downtown L'Aquila, S. Antonio, Hospital areas). In the Coppito area  $f_0$  is higher than 6 Hz, while in downtown L'Aquila is lower than 1 Hz, and a sharp N-S trending boundary between the Coppito and Hospital areas is recognizable. In the Pettino area, the  $f_0$  decreases abruptly from NE to SW. The seismic noise measurements in WAP evidenced a remarkable  $f_1$  only in the Hospital and S. Antonio areas, considering  $f_1$  the resonance frequency peak with a frequency value higher than  $f_0$  in the H/V vs frequency curves. In these areas, the measured  $f_1$  shows an amplitude comparable with the  $f_0$ . It ranges from 6 to 10 Hz and its contouring shows an NW-SE trending elongated shape following the WAP morphology (Fig. 1).

Numerical simulation. A "trial and error" iterative procedure on the inversion of HVNSR data by using the software Surface Waves (Lunedei and Albarello, 2009) has been carried out to increase points in the depth (z) vs.  $f_0$  diagram. This inversion procedure permitted to test numerically the geological cause of the observed peaks. It is based on: i) modelling surface waves; ii) assuming a flat layered viscoelastic Earth model; iii) arranging random independent point sources at the Earth surface; iv) assuming a uniform probability distribution for source location all around the single seismic station and v) using the same spectral power value of the random independent point sources for all the frequencies (e.g. 0.1-500 Hz).

Sedimentary cover (z) vs  $f_0$ : empirical correlation and mapping. The  $f_0$  values of seismic noise measurement sites located nearby the boreholes intercepting the Meso-Cenozoic bedrock were compared to z, as observed in the stratigraphic logs of these boreholes. This procedure



Fig. 2 – Quaternary sedimentary cover thickness (z) vs resonance frequency ( $f_0$ ) diagram. a: boreholes intercepting bedrock (data: 10); b: presumable sediment thickness as obtained with numerical simulations (data: 9); c: boreholes intercepting bedrock located in the proximity of the studied area (data: 8); d: Quaternary sedimentary cover thickness inferred by seismic reflection investigations in the Pettino area (Tallini *et al.*, 2012) and in an area located in the proximity of WAP (Improta *et al.*, 2012) (data: 8).

permitted to elaborate the  $z \operatorname{vs} f_{\rho}$  diagram (Fig. 2).

Other boreholes intercepting the bedrock, but located in the proximity of the studied area, and boreholes, which do not reach the bedrock, were also considered to increase data, with the purpose of defining in parametric terms the empirical relationship between thickness and  $f_0$ . In this second case, the algorithm Surface Waves of Lunedei and Albarello (2010) was take into account to compare the simulated H/V curve obtained with the software with the experimental one.

Moreover, to increase data, information of sedimentary cover thickness (z) were also obtained from seismic reflection profiles [in the Pettino area: Tallini *et al.* (2012) and in the proximity of WAP: Improta *et al.* (2012)] and by interpreting several geo-resistivity survey (GEMINA, 1963).

The number of boreholes intercepting the bedrock, which were taken into account for the z vs  $f_0$  correlation, were 10 with a variable bedrock depth ranging from 9 to 192 m; here  $f_0$  ranges from 0.7 to 10 Hz (blue spot, a in Fig. 2). In Fig. 2 other data come from different approaches:

- i) red dot (b in Fig. 2): presumable sedimentary cover thickness as obtained with numerical simulation by using the algorithm Surface Waves (Lunedei and Albarello, 2010);
- ii) green dot (c in Fig. 2): borehole intercepting bedrock located in the proximity of the studied area;
- iii) black dot (d in Fig. 2): sedimentary cover thickness inferred by seismic reflection investigations in the Pettino area (Tallini *et al.*, 2012) and in an area located southeastwards of WAP in its proximity (Improta *et al.*, 2012).

The obtained relationship is as follows:

 $z = 129.3 \cdot f^{-1.06}$ 

(1)

where the constants a and b are 129.3 and -1.06, respectively, and the coefficient R<sup>2</sup> is quite high (0.73), evidencing a good fit of data. Moreover the obtained constants a and b are quite similar to others from literature (e.g., Gosar and Lenart, 2010; D'Amico *et al.*, 2008).



Fig. 3 - Quaternary cover thickness (z) map in meters.

The contour map of Quaternary sedimentary cover thickness (z) was outlined from the  $f_0$  contour map and by using the Eq. 1 (Fig. 3).

**Conclusions.** We report the empirical correlation in the Quaternary Western L'Aquila Plain (WAP) of the velocity-depth function between the sedimentary cover thickness (z) and the seismic noise resonance frequency ( $f_0$ ), coming from a great quantity of measurements, which has been processed by applying the Horizontal to Vertical Noise Spectral Ratio (HVNSR) method.

The whole activities has beenarranged as follows: i) aquisition of approximately 800 HVNSR measurements located homogenously in the studied area; ii) elaboration of a geological and geophysical database based on boreholes data, Vs in-hole tests (cross hole, down-hole and seismic dilatometer techniques), seismic reflection investigations, georesistivity surveying and HVNSR measurements; iii) evaluation of the resonance frequency  $f_0$  from HVNSR measurements; iv) reconstruction of the  $f_0$  contour lines map; v) definition of the empirical correlation curve between the Quaternary sedimentary cover thickness (z) and  $f_0$ ; vi) reconstruction of the Quaternary sedimentary cover contour lines map (Fig. 3).

This study in the Western L'Aquila Basin (WAP) reinforces the approach that a huge quantity of geological and geophysical data can be arranged in synthetic views, which can be used as effective tools in the seismic microzonation activities for urban planning and for the estimation of the local seismic response at the site scale.

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