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### THE DEEP STRUCTURE OF THE L'AQUILA BASIN INVESTIGATED USING ARRAY MEASUREMENTS

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#### ABSTRACT

We present velocity profiles obtained through surface-wave methods in the historical city of L'Aquila (Italy). The city suffered severe damage (VIII-IX EMS intensity) during the April 6th 2009 Mw 6.3 earthquake. The area is characterized by the deep (up to 300-400 meters) basin of the Aterno river valley filled by lacustrine sediments over limestone bedrock. In downtown L'Aquila an outcropping unit basically composed of stiff conglomerates (Breccia) is over-imposed to ancient lacustrine sediments with a possible velocity inversion at a depth ranging from few tens up to one hundred meters. We deployed five 2-D arrays of seismic stations and 1-D array of vertical geophones in the city center. The 2-D arrays recorded ambient noise, whereas the 1-D array recorded signals produced by active sources. Surface-wave dispersion and spatial autocorrelation curves, calculated using array methods, were inverted through a neighborhood algorithm jointly with the microtremor HVNSR ellipticity. We obtain shear-wave velocity profiles ( $V_s$ ) representative of the southern and northern sector of downtown L'Aquila. The resulting  $V_s$  profiles are used to compare the 1-D transfer functions to aftershock data results. We apply a convolution approach evaluating synthetic time-histories in sites where surface stratigraphy is known and comparing them to recorded strong-motion data.

#### INTRODUCTION

After the April 6th 2009 Mw 6.3 earthquake, the Italian Civil Defense promoted the microzonation of the epicentral area based on geological, geophysical and geotechnical surveys. In this framework a series of 2-D geological cross-sections of L'Aquila have been produced (Fig. 1). L'Aquila historical city center is settled on a terrace composed of a quaternary conglomerates unit (Breccia) relatively stiff and consisting of limestone clasts in a marly matrix (De Luca et al., 2005). The L'Aquila terrace is bounded toward south by the Aterno river valley whereas in the north direction it is in contact with outcropping limestone. Breccia Unit (Br) is over-imposed to an ancient lacustrine sediment (L) consisting mainly of silty/sandy layers with thickness of some hundreds of meters. Br Unit is outcropping in the northern-part of downtown and along the terrace flanks, whereas in the southern part of the city very thin layers (in general thickness below 20 m) of colluvial soil (Limi Rossi; Lr) superficially overlay the Br. A deep borehole drilled approximately in the city center (S2 survey in "Piazza Duomo", see Fig. 1) documents the contact between Br and L at a depth of about 80 m, and a thickness of more than 200 meters of L (Amoroso et al., 2010). A second deep borehole at the base of terrace along the Aterno River valley (S3 survey, Fig. 1) finds a homogeneous sequence of L Unit with a thickness of 200 meters overlying the meso-cenozoic limestone bedrock. A cross-hole survey available at the same position of the S3 shows for L a shear-wave velocity profile increasing with depth: from 400 m/s in the very uppermost layer up to 800 m/s at a depth of about 80 m (Cardarelli and Cercato, 2010). A downhole survey situated in southern downtown (S8 survey, Fig. 1) shows relatively high velocities for Breccia Unit with  $V_s$  of about 1000 m/s (Working Group MS-AQ, 2010).

The L'Aquila Mw 6.3 mainshock and the strongest events of the sequence were recorded by two strong-motion stations (AQU-AQK in Fig. 2) situated respectively in the northern and southern sectors of the city center. The strong-motion records of the mainshock show peak ground acceleration (PGA) values of about 300-350  $\text{cm/s}^2$  both for horizontal and vertical components. The values of peak ground velocity (PGV) recorded at AQU and AQK range in the 35-36  $\text{cm/s}$  interval (Çelebi et al., 2010). One of main feature evidenced by seismic data recorded in the city (Milana et al., 2011) is the presence of a strong low-frequency resonance, very diffuse in the area and centered at about 0.5-0.6 Hz. This feature is related to the presence of thick layers of Br and L deposits that cannot be

easily investigated in their deepest part adopting classical geotechnical and geophysical approaches. The use of ambient vibration recorded by large 2-D arrays can be an effective tool in increasing the depth of investigation in downtown L'Aquila. Hence we performed a surface-wave analysis using ambient noise vibrations recorded by means of five 2-D arrays of seismological stations aimed at characterizing thicknesses and shear-wave velocities of the two main units (L and Br). The maximum array aperture was ranging from 100 m to about 1 km allowing a reliable surface-wave dispersion curve in a wide frequency band (1-8 Hz). Additionally, the high-frequency part (~ 8-40 Hz) of surface-wave dispersion was investigated by a linear array of geophones using an active source.

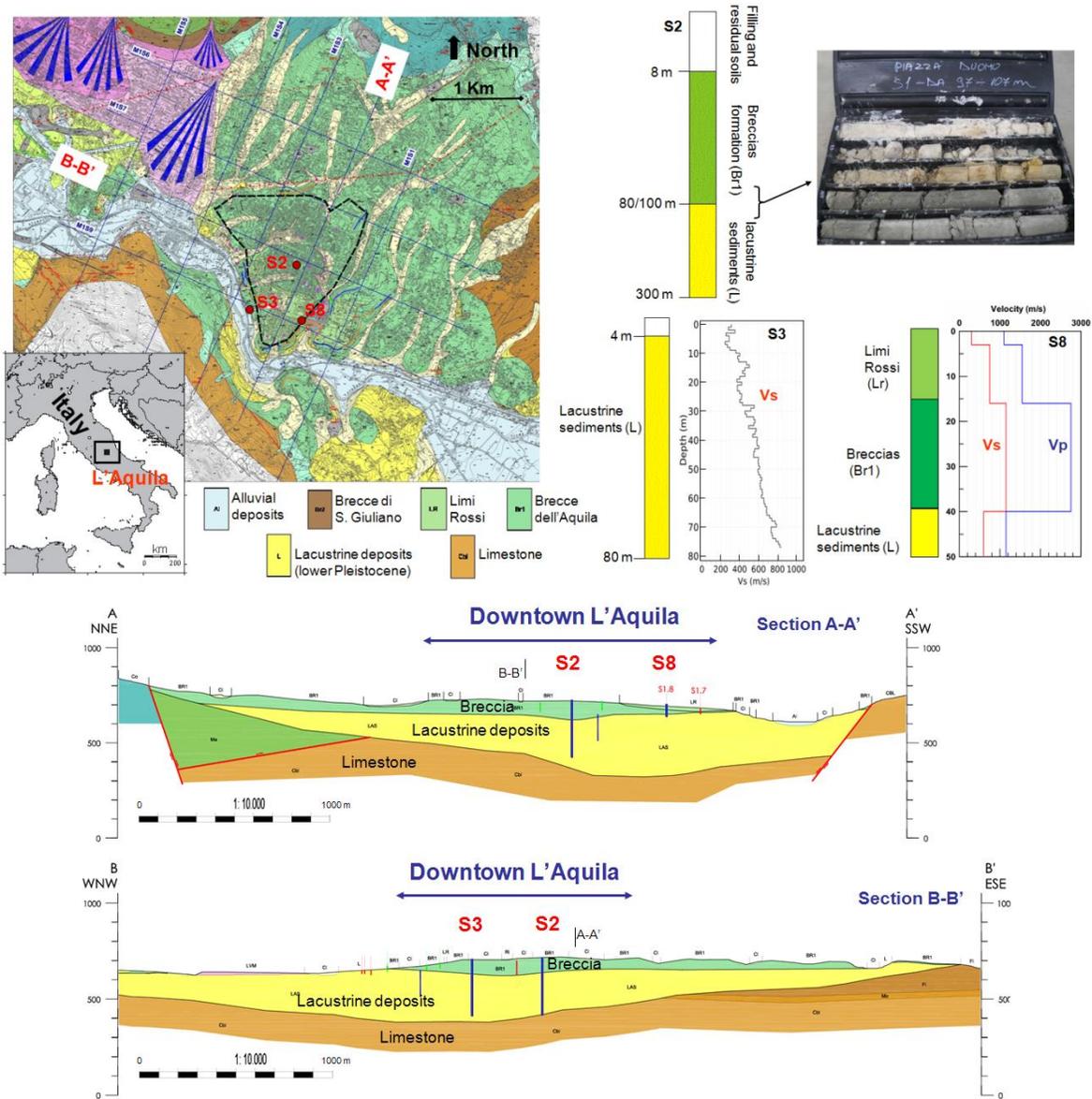


Fig. 1. Up) Geological setting of the studied area; the downtown L'Aquila is bounded by a dashed curve. On the right panel we show the S2, S3 and S8 surveys (see text). Below) The two geological cross-sections (AA' and BB') are shown.

## DATA ANALYSIS

The five 2-D arrays of seismic stations were installed in different time-periods in downtown L'Aquila (Table 1 and Fig. 2). We used different array apertures with a number of remote stations between 12 and 15 depending on the array. The seismological stations deployed approximately in a circle area were composed of a high resolution digitizer (Reftek130 or Lennartz\_MarsLite) connected to a three-component sensor (Lennartz Le3D 5s; eigenfrequency of 0.2 Hz). The sampling rate in data acquisition was fixed to 250 Hz.

The time-synchronism was supplied by a GPS antenna. To reduce the bias introduced by errors in sensors location, the position of the stations was determined by differential GPS measurements obtained performing a real time kinematic survey with a Leica Systems 1200 GNSS GPS instrument. The differential corrections were assured by a network of reference stations ([www.italpos.it](http://www.italpos.it)) connected through GPRS. With this procedure the error in station's positioning was always lower than few tens of centimeters.

The two largest arrays (AS and AN in Table 1, with maximum aperture of about 1 km) were dedicated to investigate the low-frequency range and were deployed respectively in the southern and in the northern sector of the city. In the southern area we successively arranged a 2-D array with maximum aperture of 170 m (AL in Table 1). The remaining two arrays of Table 1 (SMP and PZZ) were deployed in the northern area. In order to investigate the high-frequency range, we also performed a MASW experiment using a 1-D linear array of vertical 4.5 Hz geophones recording data from shots with different offset using a mini-gun as active source. The horizontal-to-vertical spectral ratio of ambient vibrations (HVNSR curves) were computed at each site, showing a good agreement in terms of H/V shapes within each single array (Fig. 2).

The vertical signal recorded by arrays has been analyzed through FK (Capon, 1969; Lacoss et al., 1969) and SPAC methods (Aki, 1957; Bettig et al., 2001). A joint inversion of the experimental dispersion, spatial autocorrelation, and mean HVNSR curves was performed through an improved neighbourhood algorithm (Wathelet, 2008) developed in the *geopsy* analysis tool ([www.geopsy.org](http://www.geopsy.org)).

Table 1. List of the 2-D arrays deployed in the city. Column no. 3 shows the length of synchronous signal collected by each array. Column no. 5 shows the wavenumber limits after the computation of theoretical array transfer function (Wathelet et al., 2008).

Array Name	Number of stations	Time-period of recording	Maximum aperture (m)	Kmin-Kmax (rad/m)
AS	15	20:00 -21:20 (29 November 2010)	1197	0.0082-0.11
AN	14	14:20 -16:00 (30 November 2010)	940	0.0095-0.13
AL	12	13:40 -15:10 (2 December 2010)	170	0.054-0.22
SMP	12	11:50 -13:00 (17 May 2011)	193	0.039-0.24
PZZ	12	09:30-11:30 (18 May 2011)	85	0.132-0.65

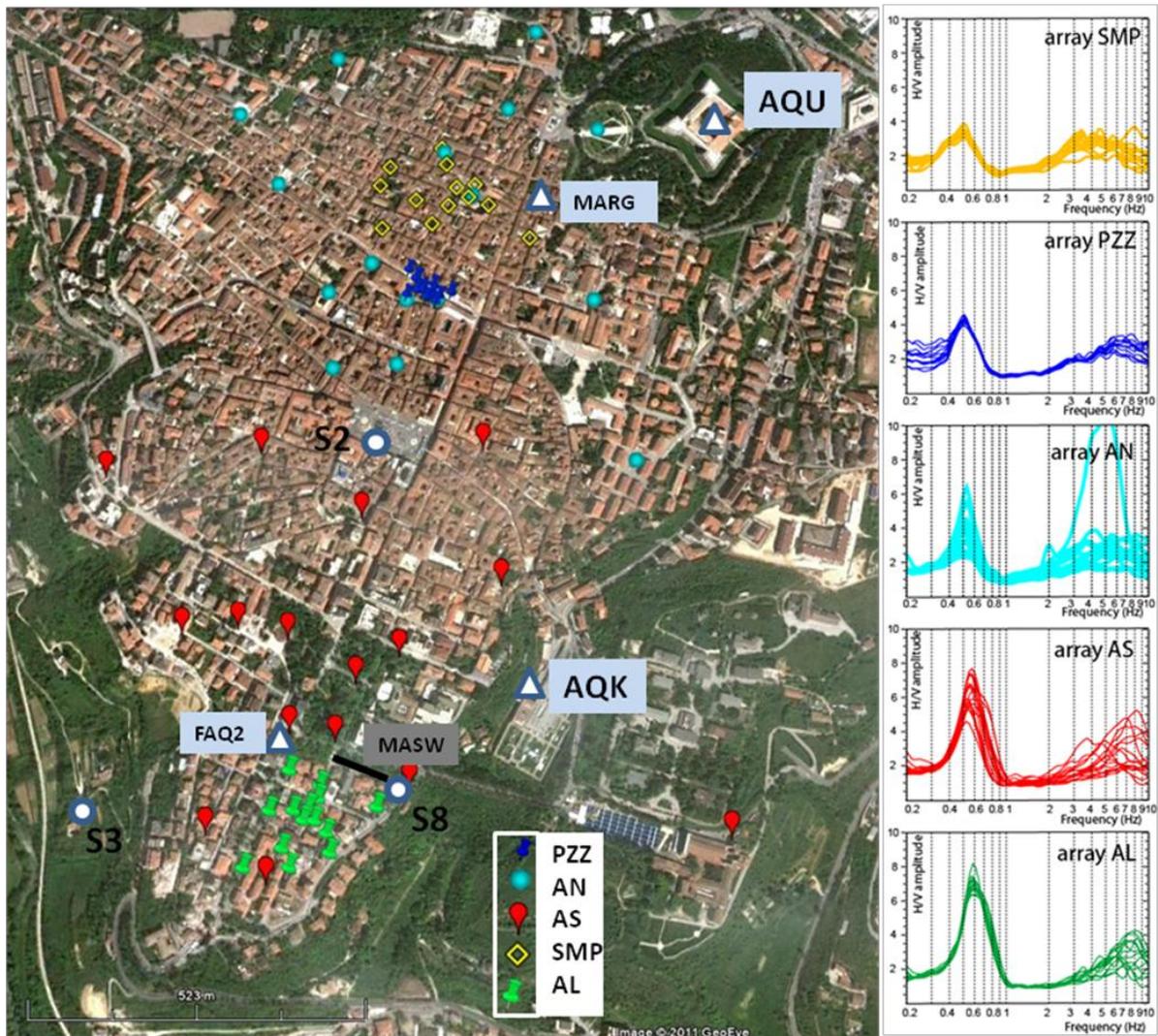


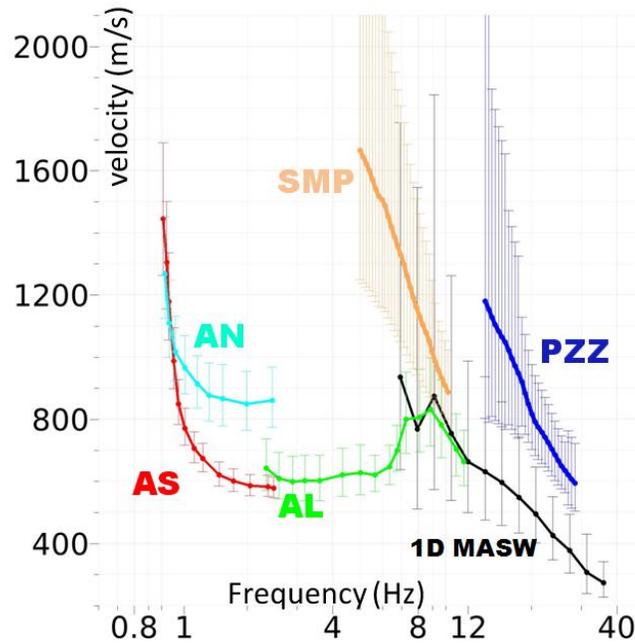
Fig. 2. Stations of the five 2-D arrays (AL, AS, AN, PZZ and SMP) installed in downtown (green, yellow, red, cyan and blue and symbols, respectively). The linear 1-D array of geophones (MASW experiment) is indicated as thick black line. The three surveys (S2, S3 and S8 of Fig. 1) are plotted as circles. The two stations that recorded the mainshock (AQR and AQU) are plotted as triangles. The H/V noise spectral ratios are also shown on the right panel.

## ARRAY RESULTS

L'Aquila is characterized by a low-frequency resonance (0.5-0.6 Hz), with a strong narrow peak in the horizontal-to-vertical spectral ratio (HVNSR curves) especially in the southern part of the city (Milana et al., 2011). The resonance frequency tends to lower values moving from South to North (from 0.6 to 0.5 Hz). The same decreasing trend is indicated by the amplitude of HVNSR curves (Fig. 2). Dispersion curves from FK analysis are shown in Figure 3. The arrays arranged in the southern part of the city (AS, AL and the 1-D MASW survey) provide consistent dispersion curves with similar velocities in the overlapping frequencies (Fig. 3). Therefore, a combined dispersion curve representative of southern downtown can be derived by merging the surface-wave dispersion curves obtained for the area. The shape of the combined dispersion curve representative of the southern part can be discussed considering three main branches. At very low frequencies (below 1.5 Hz) the surface-wave dispersion curve tends to high-velocities (about 1500 m/s), for frequencies up to 3 Hz the apparent phase-velocity is quite stable at about 600 m/s. Within intermediate frequencies (from 5 to 12 Hz), we observe an increase of the apparent phase-velocities with frequencies (from about 600 up to 800 m/s, respectively) and this could be related to an effect of a velocity reversal in the subsurface profile (i.e. corresponding to the contact between Breccias and the softer lacustrine deposits). At high-frequencies (from 10 to 40 Hz), the velocities value decreases to about 300 m/s probably caused by the presence of colluvial soil (Lr Unit).

In the northern sector, the dispersion curves provided by three arrays (AN, PZZ and SMP) show persistently larger apparent phase-

velocities than those measured in the southern area (Fig. 3). In contrast to what observed in the southern part, the dispersion curves related to the three deployed arrays are not overlapping. The largest array deployed in the northern area (AN) provides similar apparent velocities to those measured by the AS array below 1 Hz, whereas from 1 to 3 Hz the velocities derived by AN array tend to 900 m/s. The very high velocities measured by PZZ and SMP arrays cannot be merged with the dispersion curve obtained by the AN array (Fig. 3) suggesting that the local heterogeneities in the geotechnical structure play an important role in the northern area.



*Fig. 3. Surface-wave dispersion curves resulting from FK analysis. Note the good match of dispersion curves among AS, AL and the 1-D MASW data in the overlapping frequency band.*

The geotechnical information collected during the microzoning activities helped in defining the range of variability of free parameters during the inversion; for instance we assumed for the lacustrine deposit a shear-wave velocity increasing with depth by a linear gradient relationship (with  $V_s$  ranging from 400 to 900 m/s) as suggested by the S3 survey (see Fig. 1).

The velocities profiles assessed by the joint inversion, that includes dispersion and spatial autocorrelation curves and microtremor HVNSR ellipticity, are reported in Figures 4 and 5. For the city sector corresponding to southern downtown, we combined surface-wave dispersions by merging the curves from the two 2-D arrays (AS and AL) and the curve provided by the 1-D MASW survey (see Fig. 3). In the northern part of the city, we inverted the surface-wave dispersion inferred for the AN array. Because the considered arrays have a large spatial extension, the inverted profiles of Figures 4 and 5 can be considered representative of average properties of the respective areas. In both sectors, the inversion assuming the fundamental mode of Rayleigh waves is able to resolve the velocity inversion related to the contact between Br and L deposits, with the largest thickness found for northern downtown. In the inversion process for the northern arrays, it was not possible to associate the dispersion curves derived at SMP and PZZ arrays to either fundamental or higher modes of Rayleigh waves. The difficulties found in matching simultaneously the dispersion curves of northern arrays (AN, SMP and PZZ) suggest the presence of some shallow high-velocity body; this could mask the effect of a velocity inversion related to an unresolved deepest layers. Under this hypothesis we inverted the SMP and PZZ dispersion curves without considering the AN array. In this case the apparent phase-velocities, invoking a role of the first higher mode of Rayleigh wave from 15 to 25 Hz (Fig. 6), can be interpreted assuming a 50 m thick layer of Br ( $V_s$  about 1000 m/s) over imposed to an high-velocity body.

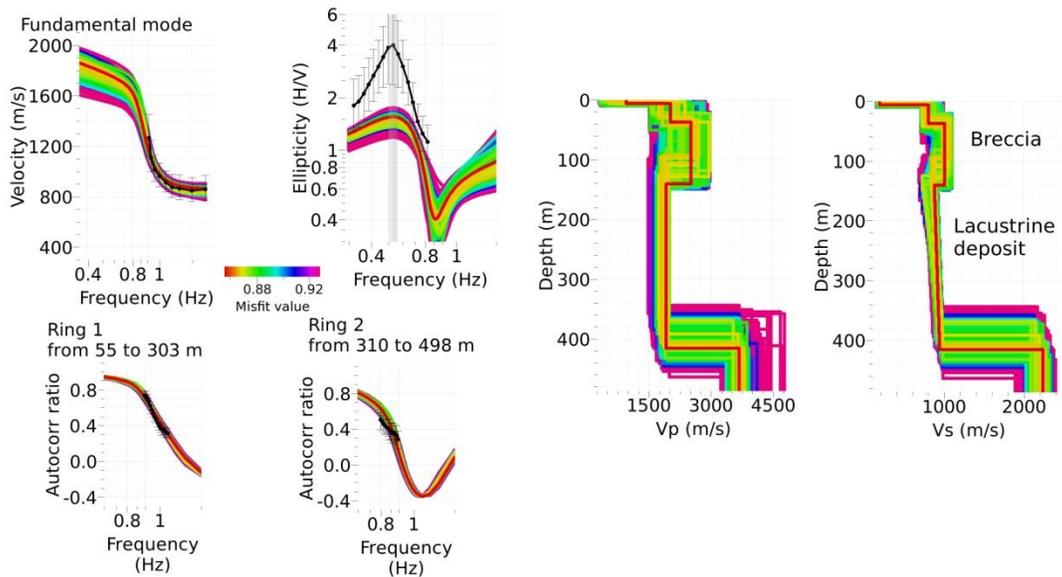


Fig. 4. Inversion results of the dispersion curve, mean HVNSR and spatial autocorrelation curves obtained for the AN array (northern downtown). The black and the colored curves show the experimental and the fitting inverted models, respectively. The resulting Vp and Vs profiles are shown on the right-hand side panel.

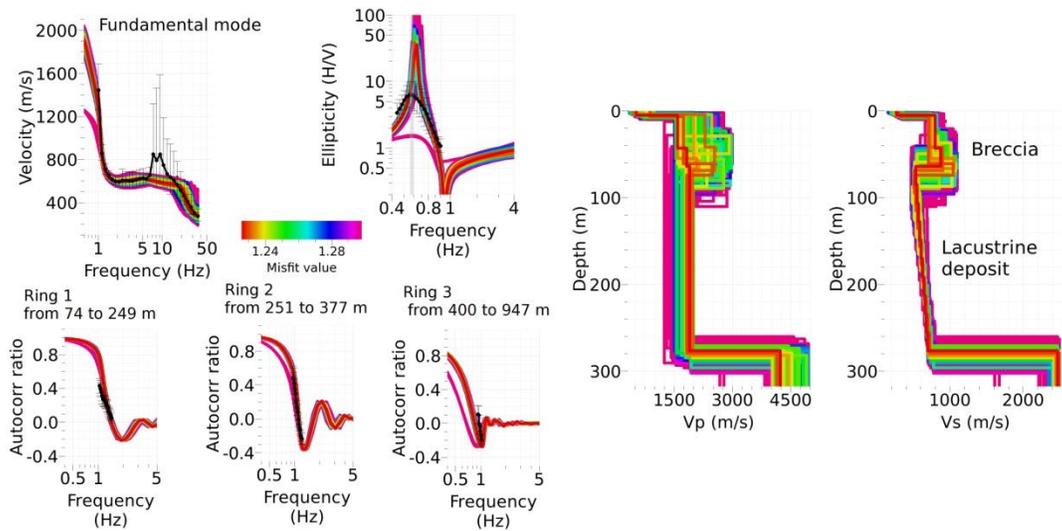


Fig. 5. Inversion results for the AS, AL and 1-D array (southern downtown). The black and the colored curves show the experimental and the fitting inverted models, respectively. The resulting Vp and Vs profiles are shown on the right-hand side panel.

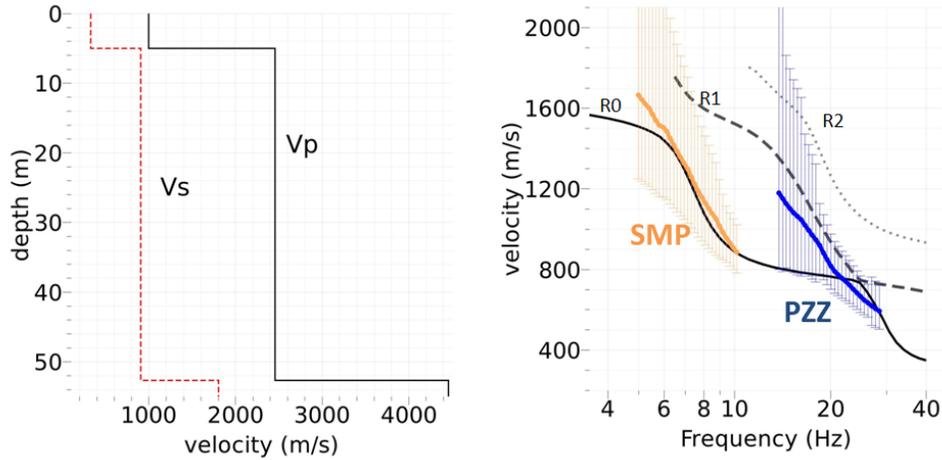


Fig. 6. Forward computation of Rayleigh dispersion curves (R0, R1 and R2 indicate fundamental, first and second higher mode of Rayleigh waves) assuming the velocity models on the left. The experimental surface wave dispersion curves inferred at SMP and PZZ arrays are also shown.

The 1-D transfer functions computed on the resulting Vs models are compared to the experimental amplification functions derived through aftershock data analysis. We considered the classical spectral ratio using a rock reference site (HHSR) of two seismic stations (FAQ2 and MARG) situated in the southern and northern sector of downtown, respectively (see Fig. 2). The HHSR at these two stations were computed on about 200 local aftershocks collected during the L’Aquila seismic sequence; the reference station was a rock site in proximity of the village ‘‘Poggio di Roio’’ 2 km SW from L’Aquila (see Milana et al., 2011). The HHSR curves are shown in Figure 7 (geometrical mean  $\pm$  1 standard deviation) and are compared to 1-D transfer functions of SH waves (vertical incidence). Although the velocity models obtained by inversion reproduced average properties over a large area, the agreement is quite good for both stations at least in terms of resonance frequency. The high frequency behavior is also sufficiently reproduced considering all the uncertainties at the base of 1-D modeling.

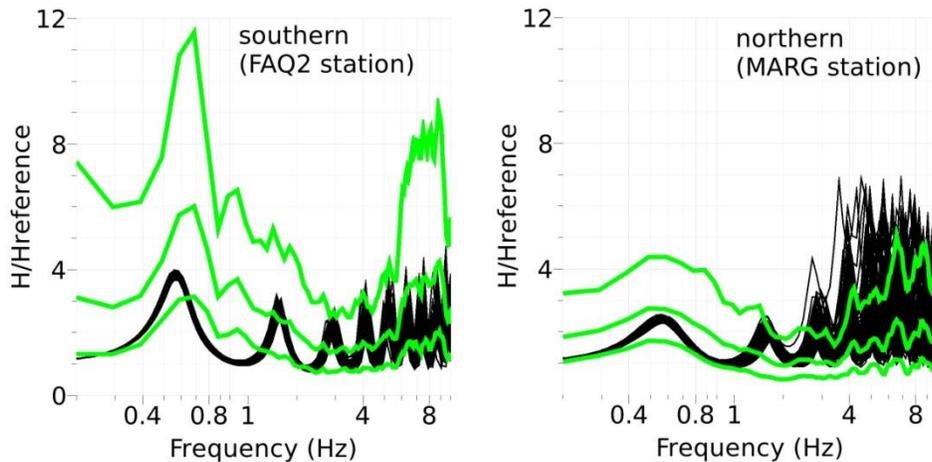


Fig. 7. Comparison between the 1-D response to vertically incident SH waves (black curves) and aftershock data analysis (green curves show the classical spectral ratio –geometrical average  $\pm$  1 standard deviation- computed for FAQ2 and MARG stations; see Milana et al., 2011). The velocities models for the computation of SH response has been provided by the inversion (Fig. 4 and 5). Q values are set equal to the velocities values divided by 10.

## BEDROCK MOTION EVALUATION

We used i) the velocity model derived for the southern sector of the city, and, ii) the L'Aquila Mw 6.3 mainshock recorded at the AQK strong-motion site (Fig. 2) to make inferences on the bedrock ground motion. The soil profile obtained by surface-wave analysis and representative of the southern part of downtown (Fig. 5) has been used to deconvolve at the bedrock level the AQK recording. The deconvolution was obtained using an equivalent-linear approach through the EERA software (Bardet et al., 2000). Due to the soil material properties we do not allow soil nonlinearity for both Br and L deposits. The deconvolution at the bedrock level of the Mw 6.3 earthquake recorded at AQK produced a reduction of PGA from 0.33 to 0.17 g and an energy decrease in the low-frequency content (Fig. 8). The bedrock-input-motion obtained by this approach can be used for determining surface strong motion synthetics at sites with a good knowledge of the near-surface geology. We applied this method to the strong motion site AQV that recorded the maximum PGA during the Mw 6.3 L'Aquila mainshock (PGA of 646 cm/s<sup>2</sup>; see Çelebi et al., 2010). AQV is situated 5 km NW from downtown L'Aquila in the middle Aterno river valley; the shear-wave velocity profile, provided by cross-hole data, shows a Vs30 value of about 475m/s (see <http://itaca.mi.ingv.it/ItacaNet/>). HVNSR results indicate a resonance frequency of 3 Hz. The near-surface geology at AQV (Fig. 9) is composed of a silty clay soil in the uppermost 5 m with Vs of 300 m/s, then a gravel layer about 25 m thick and with Vs of about 650 m/s overlaying a silty sands layer. Limestone bedrock is found at a depth of 50 m. Because nonlinear effects can occur at AQV, the convolution through an equivalent-linear approach (Bardet et al., 2000) was performed both taking into account the soil nonlinearity and adopting a constant shear modulus with no damping variation. In the former case (Fig. 9), we computed the synthetic seismogram at AQV allowing variation of shear modulus and damping ratio with shear strain. We assumed for the clay the material properties suggested by Vucetic and Dobry (1991) with plasticity index 50%, and for the sand the curves proposed by Seed et al. (1986). For the gravel layer, we adopted an average curve deduced by available literature data (Tito Sanò, personal communication).

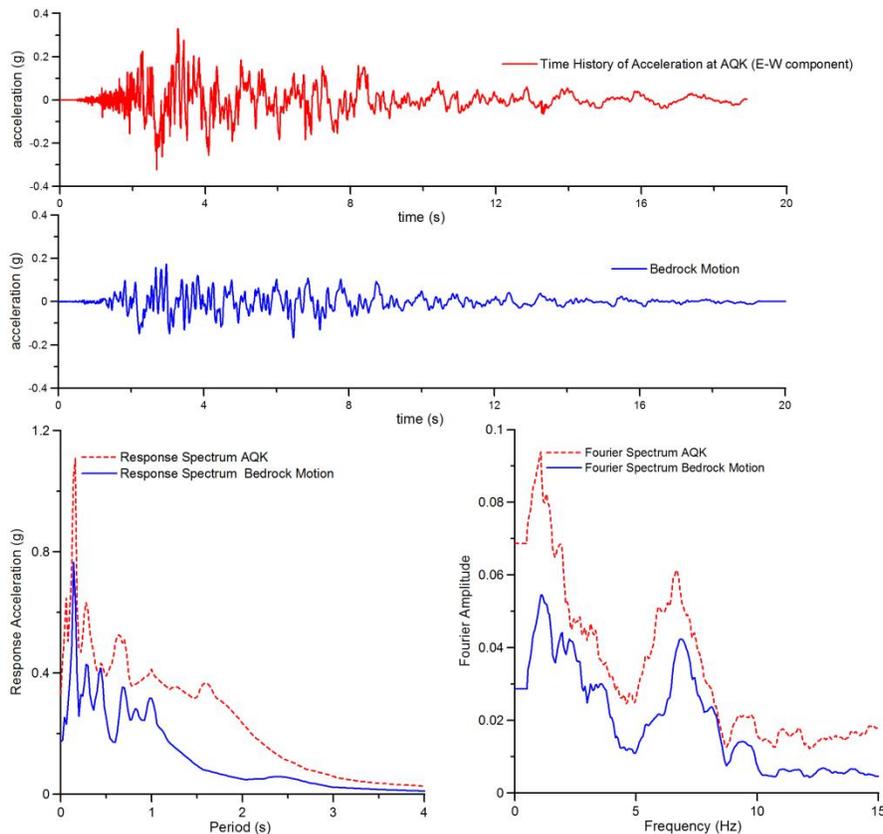


Fig. 8. Top) Comparison between the time-history recorded at AQK and the bedrock motion after the deconvolution process. Bottom) The comparison is also performed in terms of response spectra and Fourier amplitude spectrum.

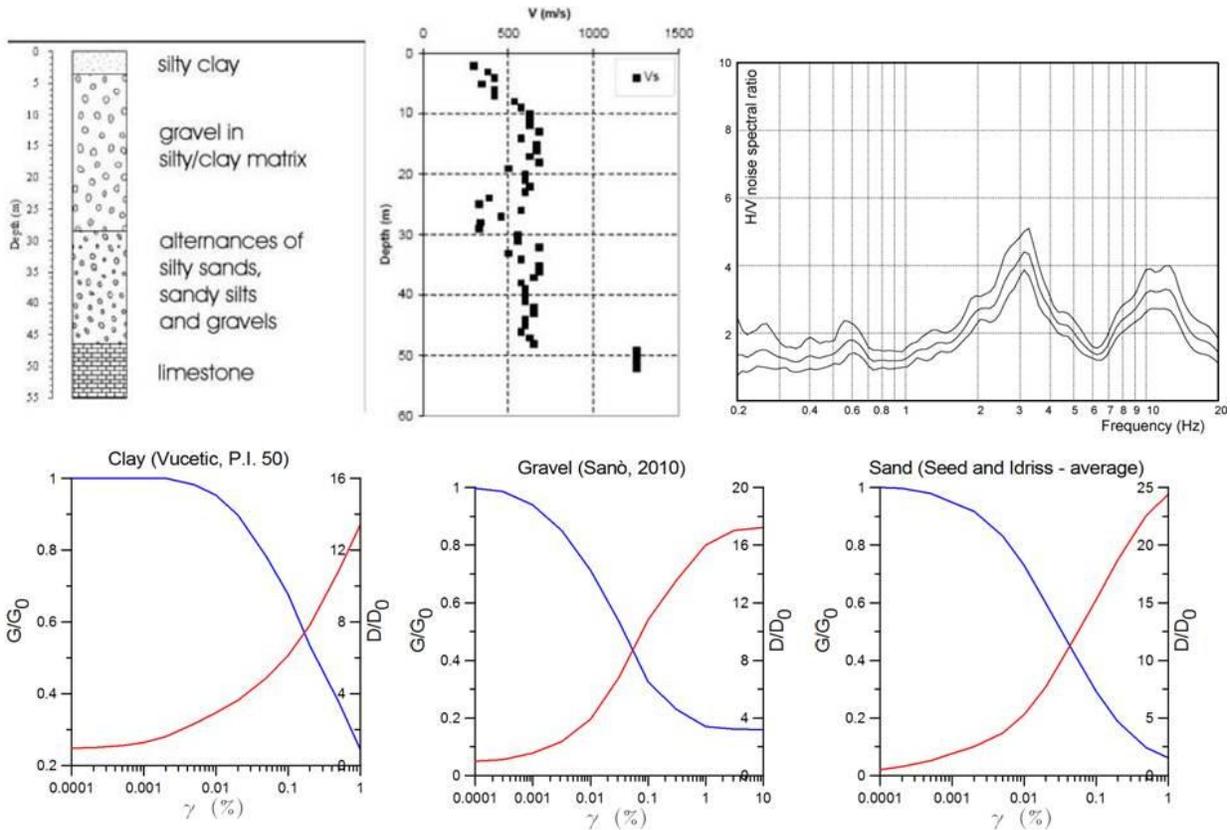


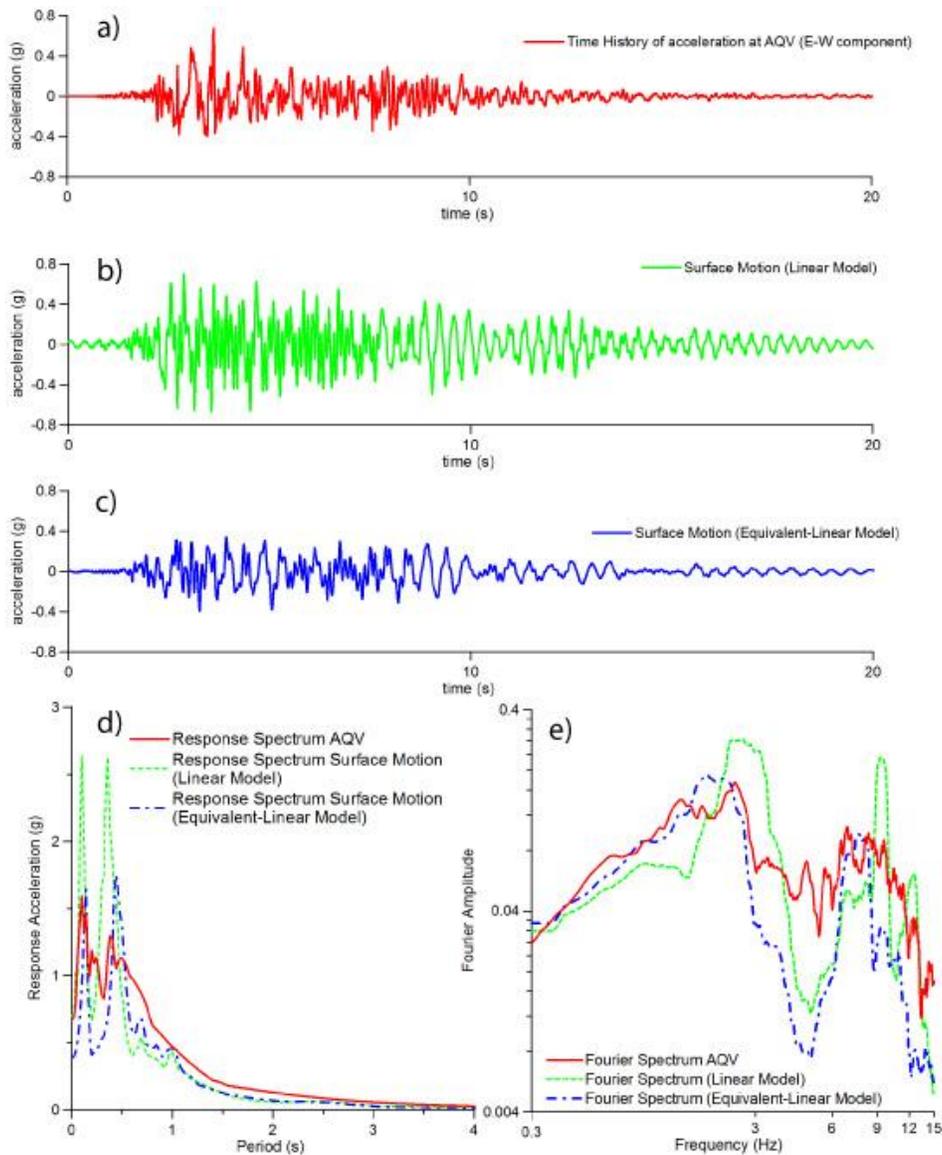
Fig. 9. Top) Soil column,  $V_s$  profile from cross-hole data and HVNSR curve at AQV site. Bottom) Normalized shear modulus and damping ratio curves used for clay, gravel and sand.

The convolution of the bedrock-input-motion with the soil column of AQV is shown in Figure 10. The result not including soil nonlinearity provides a good match of the PGA values but tends to overestimates the record's duration and the amplification at the resonance frequencies of about 3 and 9 Hz. Conversely, including soil nonlinearity we decrease the spectral ordinates at the resonance frequencies obtaining a better match between the real and synthetic spectral shapes.

## CONCLUSION

This paper shows a case-history of surface-wave analysis based on array techniques in downtown L'Aquila. Several 2-D arrays with different apertures in conjunction with 1-D array of geophones allow to derive dispersion curves in a large frequency band (0.8-40 Hz). A joint inversion provides velocity models representative of the subsurface structure of L'Aquila.

For the southern part of the city, the results indicate an effect related to a velocity inversion corresponding to the contact between stiff Breccia and ancient lacustrine deposit. Such velocity reversal is presumably associated to variation of both  $V_p$  and  $V_s$  values. In the northern part of the city, the corresponding surface-wave dispersion curves indicate a more complex situation with very high-velocity body that could mask the presence of the lacustrine deposit. We then derived the seismic input at the bedrock by deconvolving the Mw 6.3 mainshock recorded at L'Aquila using the velocity profile obtained by inversion. Then, this seismic input has been convolved with the near-surface properties of the strong-motion site (AQV) that recorded the maximum PGA during the mainshock. Although near-source and 2-D/3D effects are not considered by our analysis, a generally good agreement is observed between the ground shaking recorded at AQV and the solutions provided by the equivalent-linear model including nonlinearity.



*Fig. 10. Comparison between acceleration time-history recorded at Aqv (EW component; panel a) and the synthetic acceleration after convolution of the bedrock-input-motion with the soil column of Aqv (see Fig. 9). The modeling was performed both with and without soil nonlinearity (panel c and b, respectively). The bottom figures show the comparison in terms of response spectra and Fourier amplitude spectra (panel d and e, respectively).*

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