V_S of shallow crust structure and site effects at L'Aquila (Italy) for the *M*w 6.3, 2009 earthquake

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SUMMARY
V_S models of the shallow crust and the superficial 30 m of alluvial soils are obtained at L'Aquila from the non-linear inversion of the group velocity dispersion curves of the fundamental mode extracted from the recording of the strong event on 6 april 2009 (M_L 5.9, M_W 6.3) and active seismic experiment. They evidence the presence of very fractured carbonatic rocks, below a cover of breccias and alluvial soils. The shallowest 30m of such soils are soft with V_S of ~ 0.2 km/s.
Then ground motion is computed along a cross section by using a hybrid method consisting of modal summation and finite difference methods. After validation of the computed H/V spectral ratio with that recorded at L'Aquila (AQK station), spectral amplifications of 10-15 are computed for the vertical component and of 2-3 for the horizontal components, for a wide frequency range, corresponding to resonance frequencies of several structure typologies.

Keywords: V_S models, ground motion modelling, site effects.

1. INTRODUCTION

On April 6, 2009 a strong earthquake (M_L 5.9, M_W 6.3), hereafter named main shock, struck the Aterno Valley in the Abruzzo region (central Italy) causing heavy damage in L'Aquila and in several nearby villages and killing more than 300 people. The event had a pure normal faulting mechanism, with a rupturing fault plane NW striking and 43°- 60° SW dipping. Hypocentral location was at 9.5 km depth and epicenter at a distance of about 2 km WSW from L'Aquila center (Chiarabba et al., 2009). The overall distribution of the aftershocks defined a complex, 40 km long and 10-12 km wide, NW trending extensional structure. The area has a high seismic hazard level in Italy and has experienced in the past destructive earthquakes such as the 1349, I=IX–X; the 1461, l'Aquila, I=X and the 1703, I=X (CPTI working group, 2004). Many active faults are recognized in the area and several of them are indicated as potential sources for future moderate and large earthquakes by several authors (see for a review Galli et al., 2008).
The 2009 seismic sequence was recorded by accelerometers of Rete Accelerometrica Nazionale (RAN) network, managed by the Italian Civil Defense Department, some of which located at L'Aquila (AQK station) or in the NW of it (AQG, AQA, AQM, AQV stations) (Fig. 1.1). They are equipped with three-component sensors set to 1 or 2 g full-scale, coupled with high resolution digitizers.
L'Aquila is located in the Aterno river basin, a complex geological structure with a carbonate basement outcropping along the valley flanks and elsewhere buried below alluvial and lacustrine deposits with variable thickness. The surface geology is even more complicated by the presence of breccias consisting of limestone clasts in a marly matrix. Such complex geological scenario reflected in a large spatial variability of amplitude and frequency content of the ground motion (e.g. Cultrera et al., 2011). Non-linear behaviour of soft clay and peat soils at Aterno valley has been estimated for peak ground acceleration ≥ 0.1g (Nunziata et al., 2012).
In order to estimate realistic ground motion we need physical parameters of rocks from surface to depths greater than the earthquake hypocenter. At regional scale, a physical model is available extending to depths of about 300 km (Brandmayr et al., 2010).

At engineering scale, after the 2009 seismic sequence, geological and geophysical studies, beside several drillings with down-hole tests generally reaching depths around 25-30 m, have been performed at L'Aquila to reconstruct the shallow 200-300 m of subsoil (Gruppo di Lavoro MS-AQ, 2010). The new interpretation of available gravity data indicated a meso-cenozoic carbonate unit (average density=2.6 g/cm^3) lying at maximum depth of 200-300 m in the Aterno valley, below flysch or breccia unit (average density=2.4 g/cm^3) and Quaternary products including alluvial and lacustrine deposits and fan alluvial material (average density=1.9 g/cm^3). Strong lateral and vertical geological heterogeneities have been evidenced which, in the center of L'Aquila, are mainly due to a discontinuous stiff top layer of breccias, called megabreccias, overlying soft lacustrine sediments. The geometry of the vertical and lateral passage of the lacustrine to megabreccia deposits is still poorly known due to the shallow drillings.

The analysis of strong and weak motion recordings in 1996-98 put in evidence amplification effect at low frequencies (0.6 Hz) in the town of L'Aquila and 2D numerical modeling allowed to fit it along a SW-NE section (De Luca et al., 2005). A sedimentary basin was inferred, filled by lacustrine sediments, with a maximum thickness of about 250 m, below the megabreccias formation about 50 m thick.

Spectral H/V ratios of the horizontal and vertical components computed for several earthquakes during the 2009 seismic sequence evidenced a strong variability of the main peak frequency, but at the station at L'Aquila (AQK) (e.g., Nunziata et al., 2012) for which the resonance frequency (0.6 Hz) is the same observed from the analysis of strong and weak motion recordings in 1996-98 (De Luca et al., 2005).

Aim of this paper is to evaluate site effects at L'Aquila town for the main shock. First we define V_S models of the shallow crust and build a realistic geological-seismic cross section from the main shock epicentre and passing through the recording AQK station. Then simulation of the ground motion is performed by the Neo-Deterministic Seismic Hazard Analysis (NDSHA) approach and site effects are evaluated after validation of the computed resonance frequency with that retrieved from the main peak of the recorded H/V spectral ratio at the AQK station.

2. V_S MODELS

The crucial point of a sounded evaluation of site amplification effects is the definition of representative V_S models of the geological structures. The most appropriate method with single signals is that based on the non-linear inversion of Rayleigh wave group velocities (e.g., Nunziata et al., 2004; Nunziata, 2007).

2.1 Methods

The group velocity is measured as function of period by the Frequency Time Analysis (FTAN) on single waveforms (e.g. Levshin et al., 1989; Nunziata, 2010). The FTAN method allows to isolate the different phases in a seismogram, in particular the fundamental mode of surface waves. A system of narrow-band Gaussian filters is employed, with varying central frequency, that do not introduce phase distortion and give the necessary resolution in the time-frequency domain. The source-receiver distance is commonly assumed to be the epicenter distance when it is much greater than the event depth. When this assumption is not valid, in order to extract the correct dispersion curve of Rayleigh waves we have to add a time delay to seismograms as $\Delta t=h/V_P$, *h* being the source depth, V_P the average P-wave velocity from surface to the hypocenter, and then analyze the seismograms by FTAN, considering the hypocenter distance (e.g. Natale et al., 2005 and references therein).

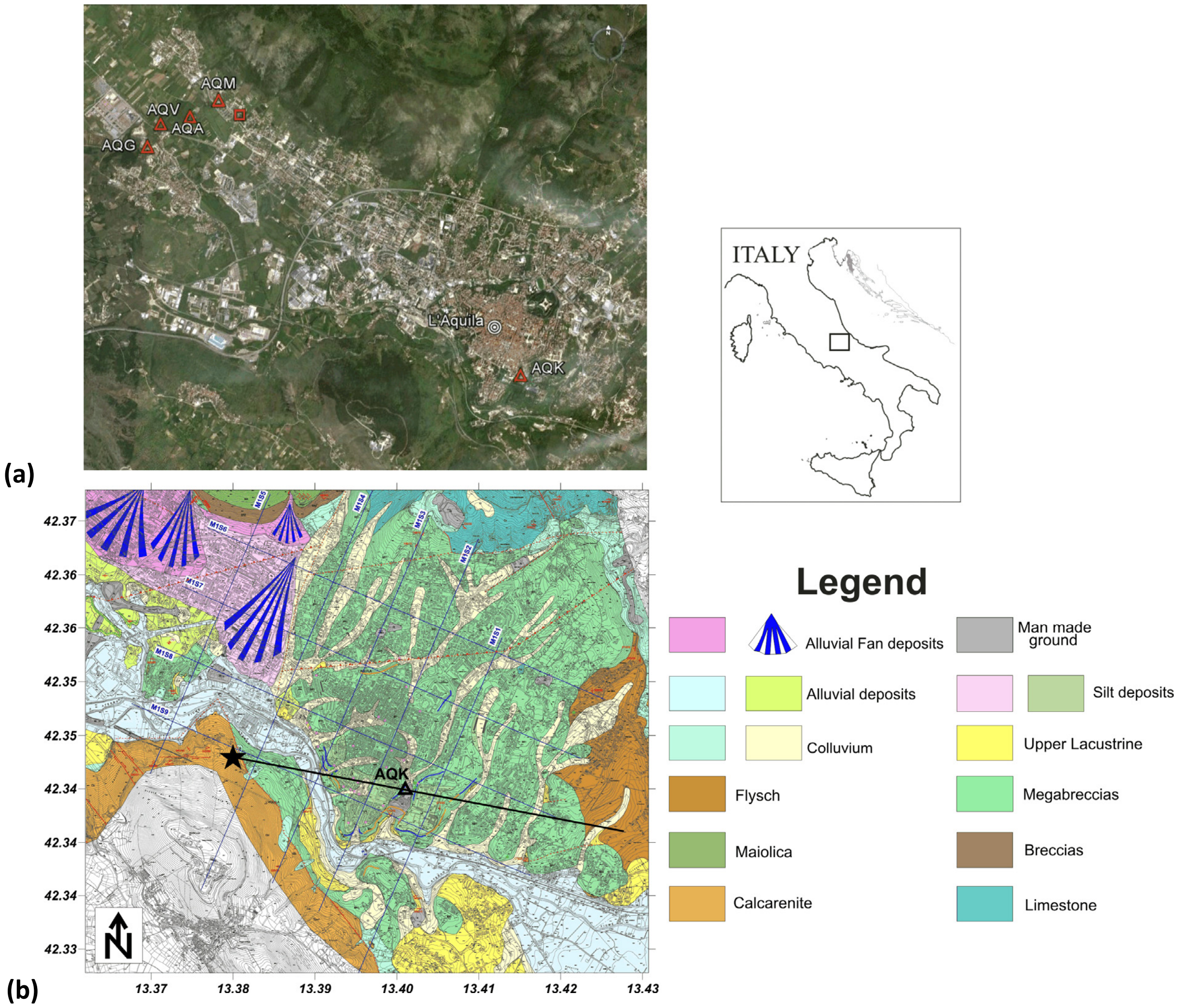


Figure 1.1. (a) Location of the recording RAN stations (triangles) and the site of the active seismic experiment (square); (b) Location of the cross section at L'Aquila on the geological map 1:6000 (Protezione Civile, 2009). The star represents the 6 April 2009 mainshock ($M_W = 6.3$) epicenter (Chiarabba et al., 2009).

The dispersion curves obtained in such a way can be inverted to determine S-wave velocity profiles versus depth. A non-linear inversion is made with the Hedgehog method (Panza, 1981; Nunziata, 2010 and references therein) that is an optimized Monte Carlo non-linear search of velocity-depth distributions. In the inversion, the unknown Earth model is replaced by a set of parameters and the definition of the structure is reduced to the determination of the numerical values of these parameters. In the elastic approximation, the structure is modeled as a stack of N homogeneous isotropic layers, each one defined by four parameters: V_P (dependent parameter), density (fixed parameter), V_S and thickness (independent parameters).

Given the error of the experimental phase and/or group velocity data, it is possible to compute the resolution of the parameters (parameter step), computing partial derivatives of the dispersion curve with respect to the parameters to be inverted (Nunziata, 2010 and references therein). The theoretical phase and/or group velocities computed during the inversion with normal-mode summation are then compared with the corresponding experimental ones and the models are accepted as solutions if their difference, at each period, is less than the measurement errors and if the r.m.s. (root mean square) of the differences, at all considered periods, is less than a chosen quantity (usually 60–70% of the average of the measurement errors). Being the parameter step indicative of the parameter resolution, all the solutions of the Hedgehog inversion differ by no more than ±1 step from each other. A good rule of thumb is that the number of solutions is comparable with the number of the inverted parameters. From the set of solutions, we accept as representative solution the one with r.m.s. error closest to the average r.m.s. error of the solution set, and hence reduce, at the cost of loosing in resolution, the projection of possible systematic errors (Panza, 1981) into the structural model. Other selection criteria of the representative solution are discussed in detail by Boyadzhiev et al. (2008).

2.2 Earthquake recording

Time corrections have been applied to the main shock recording by assuming the regional average V_P (5.2 km/s) computed from the V_S model relative to the cell 1°x1° containing L'Aquila (Brandmayr et al., 2010), assuming a V_P/V_S ratio of 1.8. Such value is in very good agreement with those used by INGV (5 km/s) and Chiarabba et al. (2009) (V_P=5.5 km/s) for earthquake location and attributed to the shallow 11.1 km of crust.
Dispersion curves of Rayleigh wave fundamental mode have been extracted from the vertical and radial components of main shock recording (Fig. 2.1). The average dispersion curve, defined in the period range of 0.4-1.4, has been inverted with Hedgehog method (Panza, 1981; Nunziata, 2010 and references therein) to get V_S models. A V_P/V_S ratio equal to 1.8 turned out to be a suitable value after a set of tests made varying it between 1.8 and 2.1. In other words, keeping all other values of the parameterization unchanged, the number of solutions maximizes for V_P/V_S=1.8. V_S models of the shallow 1 km have been obtained. The representative solution presents velocities increasing from 0.85 to 1.45 km/s at about 0.5 km of depth, with a low velocity layer, 60 m thick, with V_S of about 0.70 km/s (Fig. 2.1). Taking into account the geological data relative to the shallowest 0.2-0.3 km (Gruppo di Lavoro MS-AQ, 2010), stratigraphies may be attribuited to the V_S profiles. Alluvial soils are sandwiched between megabreccias and calcarenites. These velocities are in agreement with literature data (De Luca et al., 2005), but for those of calcarenites being ours (V_S = 1.45 km/s) lower (V_S=2.5 km/s).

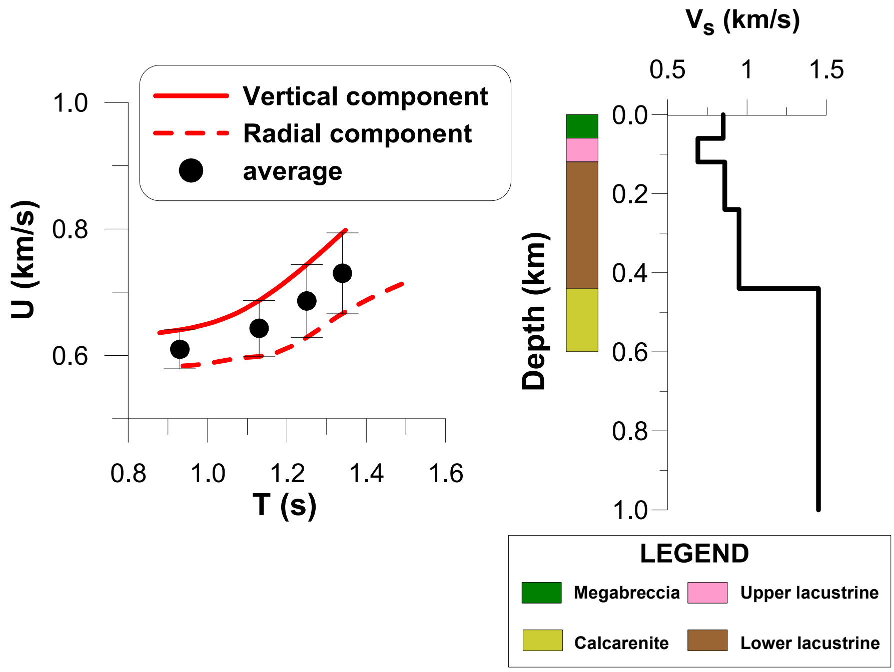


Figure 2.1. Rayleigh waves group velocity dispersion curves of fundamental mode extracted by FTAN method from radial and vertical components of the recorded main shock at the AQK station (on the left); V_S velocities obtained from the non-linear inversion (Hedgehog method) of the average dispersion curve with interpretative stratigraphy (on the right).

2.3 Active seismic experiment

V_S models have been also retrieved from an active seismic experiment performed in the Coppito area (Fig. 1.1) with geophone offsets of 64 m and by using FTAN and Hedgehog methods. The models are characterized by an average velocity (V_{S30}) of 190 m/s in the shallow 30 m of alluvial soils (Fig. 2.2b). Instead a V_{S30} of 473 m/s is obtained from a cross-hole test, 500 m distant, performed close to the AQV station, in the same alluvial soils (Puglia et al., 2011). Such discrepancy has important consequences in the respect of the national building code as the soil classification changes from C to B (Nuove norme tecniche per le costruzioni, 2008).

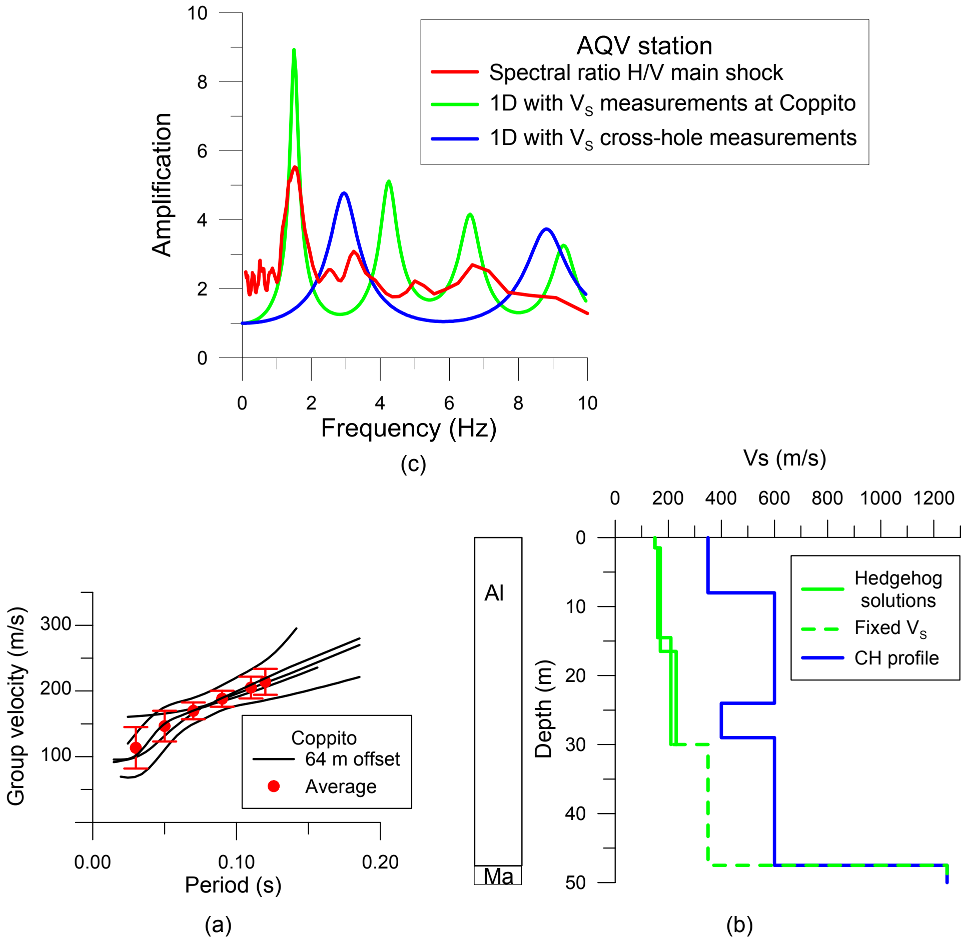


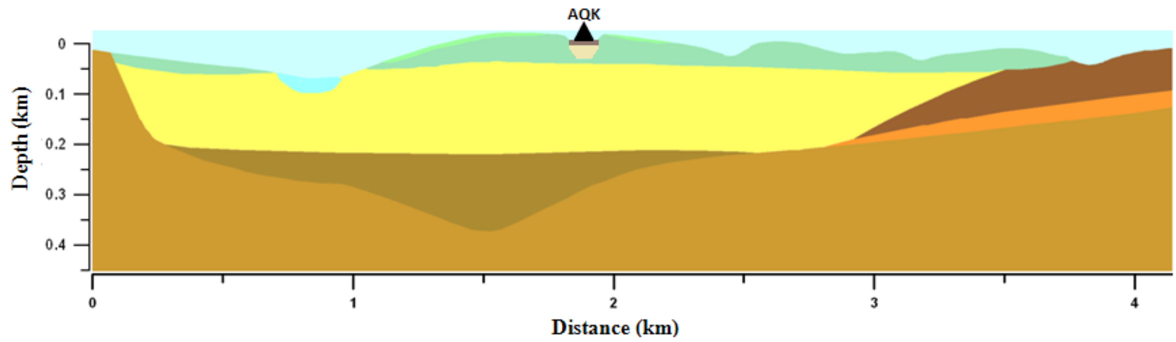
Figure 2.2. (a) Rayleigh waves group velocity dispersion curves of fundamental mode extracted by FTAN method from signals of active seismic experiment at Coppito (location in Fig. 1.1a); (b) V_S velocities obtained from the non-linear inversion (Hedgehog method) of the average dispersion curve (a) as compared with Cross-Hole (CH) measurements at the AQV station site (Puglia et al., 2011) (location in Fig. 1.1a); (c) Comparison between the resonance frequency estimated from the spectral ratio H/V of the main shock recorded at the AQV station and the 1D amplifications (SHAKE program) computed by assuming the V_S profiles in (b).

The comparison of the frequency of the maximum peak of the H/V spectral ratio, relative to the main shock recorded at the AQV station, with the 1D spectral amplifications, computed with SHAKE program (Schnabel et al., 1972), by assuming the two different V_S data sets has evidenced the agreement with the V_S profiles relative to FTAN-Hedgehog measurements (Fig. 2.2c). Once more, such comparison evidences: 1) the strong lateral and vertical heterogeneities of such alluvial soils; 2) the cross-hole (and down-hole) point-like measurements, even though quite precise, may not be representative of the average seismic path (e.g. Nunziata et al., 2004; Nunziata, 2007). We remind that the surface measurements for the FTAN analysis do not need boreholes or conventional arrays, hence are particularly suitable in the urban areas.

3. GROUND MOTION MODELLING

Simulations of the 2009 L'Aquila main shock have been performed with the Neo-Deterministic

Seismic Hazard Analysis (NDSHA), an innovative modelling technique that takes into account source, propagation and local site effects (for a recent review see Panza et al., 2011).
This approach uses a hybrid method consisting of modal summation and finite difference methods (Panza et al., 2001 and references therein). The path from the source up to the region containing the 2-D heterogeneities is represented by a 1-D layered anelastic structure. The resulting wavefield for both SH- and P-SV- waves is then used to define the boundary conditions to be applied to the 2-D anelastic region where the finite difference technique is used. Synthetic seismograms of the vertical, transverse and radial components of ground motion are computed at a predefined set of points at the surface. Spectral amplifications are computed as response spectra ratios, RSR, i.e. the response spectra computed from the signals synthesized along the laterally varying section (2D) normalized by the response spectra computed from the corresponding signals, synthesized for the bedrock (1D). A scaled point-source approximation (Gusev, 1983 as reported in Aki, 1987) has been considered to scale the seismogram to the desired scalar seismic moment. Due to the short epicentral distance, a greater distance (6 km) has been assumed in the computation of the ground motion.



Legend

Name	Density (g/cm^3)	V_P (km/s)	V_S (km/s)	Q_P	Q_S
Air	0	0	0	0	0
Colluvium	1.7	0.500	0.250	110	50
Alluvial deposits	1.7	0.500	0.250	110	50
Silt deposits	1.7	0.400	0.200	110	50
Megabreccias	2.0	1.620	0.900	220	100
Upper Lacustrine	1.9	0.950	0.500	220	100
Lower Lacustrine	1.9	1.240	0.650	220	100
Sandstone	2.0	1.620	0.900	220	100
Marls	2.2	2.610	1.450	220	100
Calcarenite	2.2	2.610	1.450	220	100

Figure 3.1. Computing cross section at L'Aquila through the AQK station with the physical parameters attributed to lithotypes.

Modelling of the main shock has been done along a geological cross section at L'Aquila, from the epicentre through the AQK station (Fig. 3.1). Along the 2D model, the outcropping units are represented by megabreccias except in the Aterno river, where recent fluvial sediments are present. Megabreccias are on the top of lacustrine clays which overlay a rock basement represented by the calcarenites. Literature V_S (De Luca et al., 2005) have been attributed to upper and lower lacustrine soils. At greater depths, physical properties of rocks have been assigned according to the regional model (Brandmayr et al., 2010). A parametric study has been done for the best dip angle between 43° and 60°. A dip of 56° turned out to be able to fit the observed response spectra and is in agreement with the geometry of the seismogenic fault (Galli et al., 2009). A small valley of colluvium had to be hypothesized beneath the AQK station, realistically assumed on the basis of geological considerations, in order to fit the observed response spectra and the frequency of the main peak of the H/V spectral ratio obtained from the main shock recording at the AQK station (Fig. 3.2).
It is important to evidence that the vertical spectral accelerations are comparable with the horizontal ones, which is still not included in the Italian seismic code. The resonance frequency is lower than 1 Hz along the cross section, except in the ending portion where soft rocks are present (Fig. 3.3).

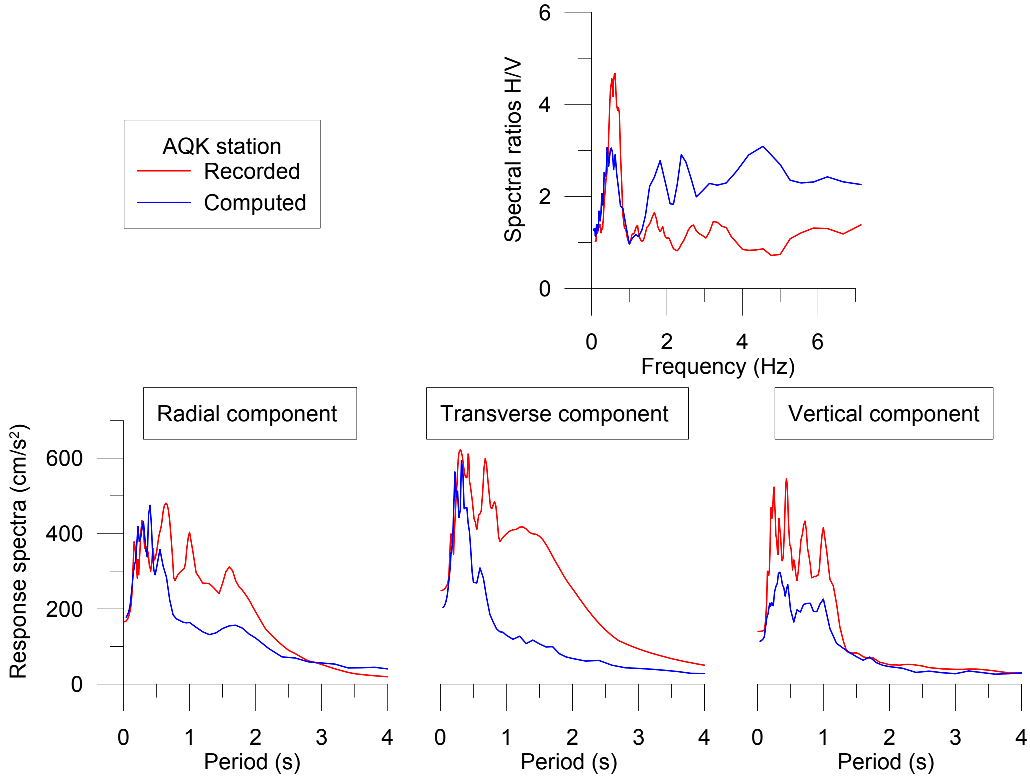


Figure 3.2. Comparison at the AQK station of the computed and recorded main shock: (top) H/V spectral ratio; (bottom) response spectra computed for 5% damping.

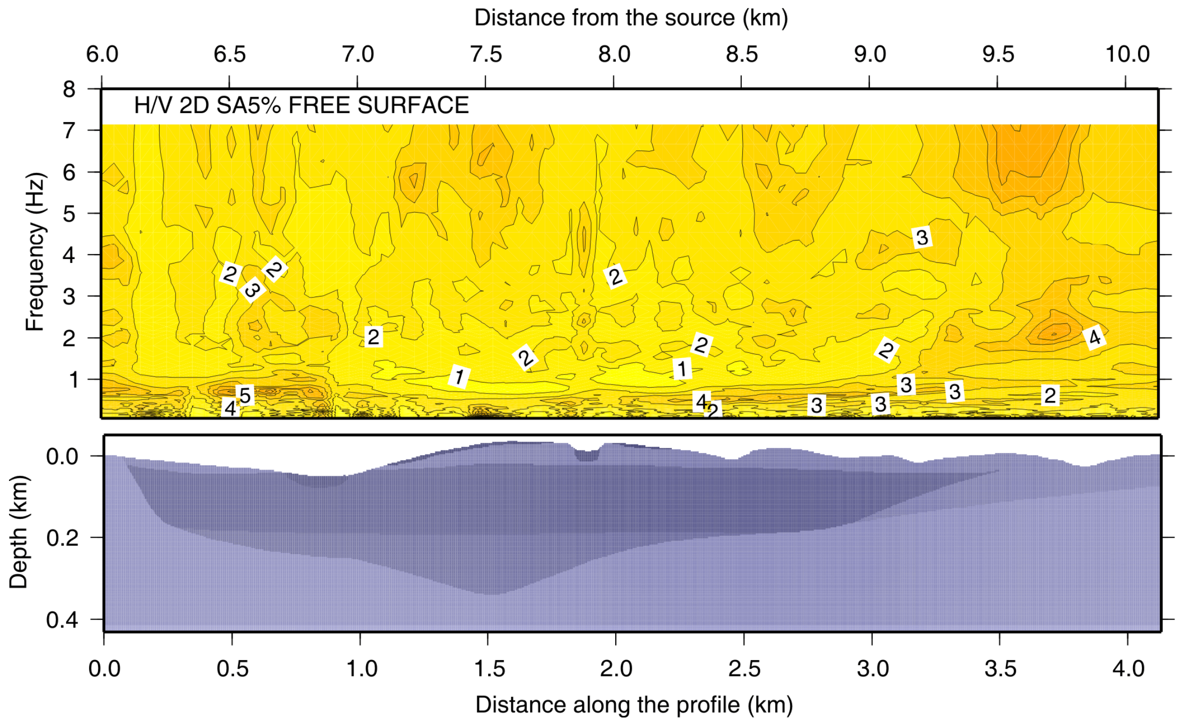


Figure 3.3. H/V spectral ratios computed along the cross section at L'Aquila

Spectral amplifications greater than 10 are computed for the vertical component of ground motion at frequencies lower than 1 Hz and of about 5 at 4 Hz in correspondence of the Aterno river alluvial sediments (Fig. 3.4). As regards the radial and transverse components, spectral amplifications of 2-3 result for a wide frequency range (2-5 Hz), in correspondence of the colluvium and alluvial deposits.

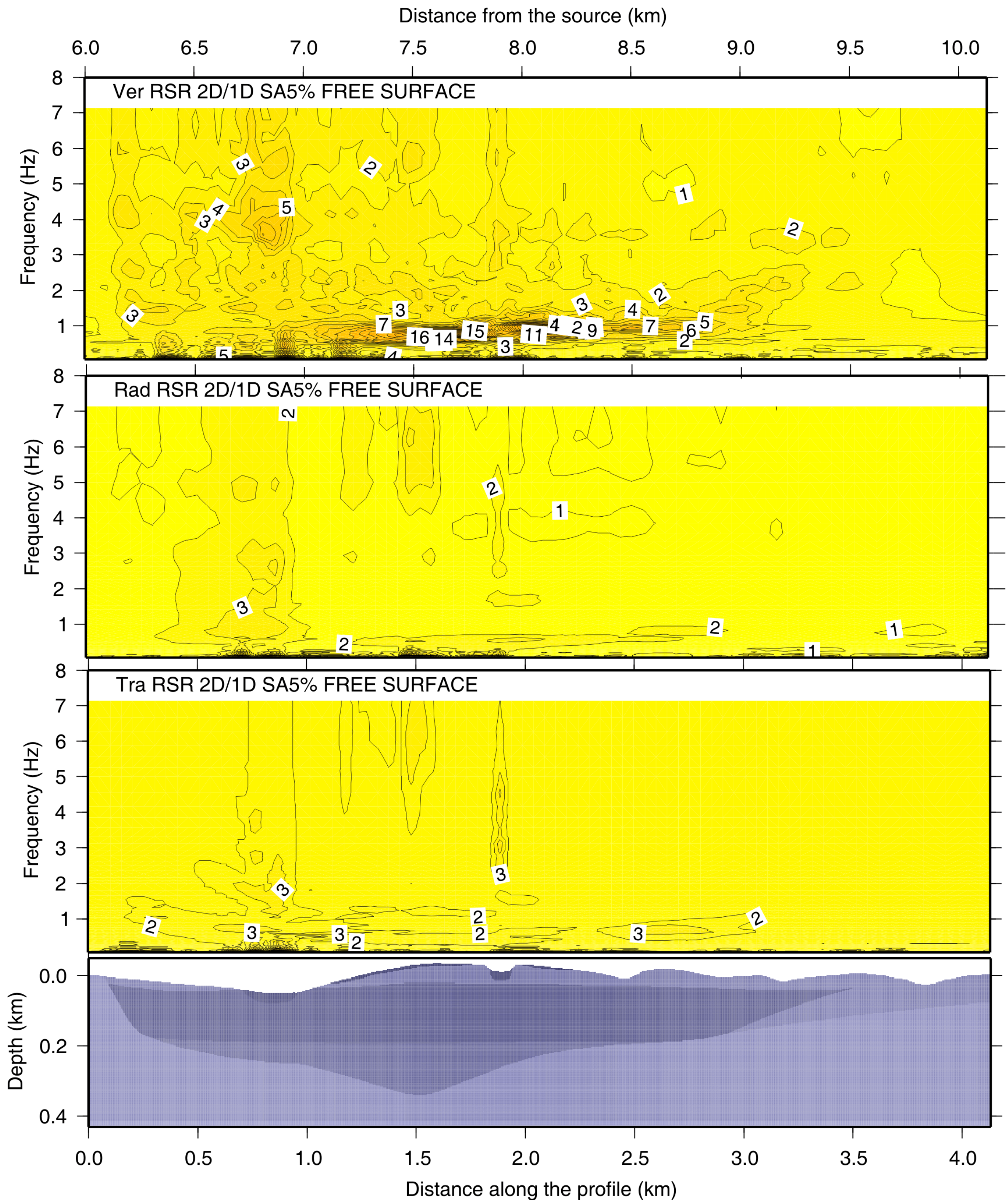


Figure 3.4. Spectral amplifications (RSR 2D/1D) along the cross section at L'Aquila. Response spectra are computed for 5% damping. From the top vertical, radial and transverse components of the computed ground motion.

4. CONCLUSIONS

A realistic estimation of the ground motion at L'Aquila for the M_W 6.3 earthquake is obtained by the NDSHA approach, an innovative modelling technique that takes into account source, propagation and local site effects (Panza et al., 2001; 2011). Another key point is the definition of V_S models representative of the seismic path, like those obtained from the non-linear inversion of Rayleigh group velocities. The soundness of the synthetics is in the good fitting of the recorded H/V spectral ratio and response spectra, despite the point-source approximation. The lateral and vertical geological variability mainly due to the covering of megabreccias on soft soils are responsible of spectral amplifications, mostly for the vertical component, for a wide frequency range (0.5-5 Hz). Taking into account that the majority of the buildings, generally 2-5 floor, at the historical center of L'Aquila suffered serious damage, we can argue that spectral amplifications might have been responsible for damage, beside the near-field conditions.

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