Evaluation of Linear and Nonlinear Site Effects for the M_W 6.3, 2009 L'Aquila Earthquake

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1. Introduction

An effective strategy for the seismic risk mitigation needs the use of advanced seismological methodologies for a realistic estimate of the seismic hazard and, consequently, to reduce earthquake damage through a preventive evaluation of vulnerability and actions for structure safety. Prediction of earthquakes and their related effects (expressed in terms of ground shaking) can be performed either by a probabilistic approach or by using modelling tools based, on one hand, on the theoretical knowledge of the physics of the seismic source and of wave propagation and, on the other hand, on the rich database of geological, tectonic, historical information already available. Strong earthquakes are very rare phenomena and it is therefore statistically very difficult to assemble a representative database of recorded strong motion signals that could be analyzed to define ground motion parameters suitable for seismic hazard estimations. That is, the probabilistic estimation of the seismic hazard is a very gross approximation, and often a severe underestimation, of reality.

A realistic and reliable estimate of the expected ground motion can be performed by using 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 is done using basic principles of physics about wave generation and propagation in complex media, and does not require to resort to convolutive approaches, that have been proven to be quite unreliable, mainly when dealing with complex geological structures, the most interesting from the practical point of view.

The NDSHA approach has been used, among others, in the framework of the UNESCO-IUGS-IGCP project 414 "Seismic Ground Motion in Large Urban Areas", to evaluate ground motion of a group of Large Urban Areas and Megacities in the world representative of a broad spectrum of seismic hazard severity (Panza et al., 2004).

A M_W 6.3 earthquake struck on 6 April 2009, at 01.32 GMT, the Abruzzo region (central Italy). The L'Aquila town, located few km northeast to the main shock epicentre, and several villages located nearby, suffered heavy damages and the casualties were about 300. The damage level generally corresponded to intensity ≤ VIII MCS, with few maximum values ≥

IX MCS generally associated to construction vulnerability and, in some cases, to site amplification effects (Fig. 1).

In the past, destructive earthquakes originated in the L'Aquila basin such as the 1349, I=IX–X; the 1461, L'Aquila, I=X and the 1703, I=X (CPTI working group, 2004). Seismic hazard maps based on geological fault slip-rate data show that strong events (intensities ~IX) can hit L'Aquila with short recurrence time of approximately 250±50 years (Roberts et al., 2004). Boncio et al. (2004) estimated a maximum expected earthquake magnitude of 6.1–6.4 for the L'Aquila fault segment in Paganica, and stronger events are expected for other segments of the same fault system or other neighboring faults for their impressive post-glacial fault scarps (Papanikolaou et al., 2010 and references therein). Based on trenching investigations, Galli et al. (2002) support that the Campo Imperatore fault, only 20 km away from L'Aquila, can give a Magnitude 7.0 earthquake. Moreover, the 1703 (M_W ~6.7) earthquake produced surface ruptures >10 km and a maximum vertical displacement of 1m in the neighbouring Arischia fault (Blumetti, 1995). These ruptures are almost one order of magnitude larger than the ruptures produced by the 6 April L'Aquila earthquake (0.1-0.3 m), implying that the surrounding faults have the capacity to generate significantly stronger events.

For seismic hazard assessment, in order to prevent damage from even more energetic and dangerous earthquakes at L'Aquila, it is necessary to compute realistic seismograms.

Aim of this paper is to compute the seismic ground motion at L'Aquila for the 6 April 2009 earthquake by the NDSHA approach and evaluate nonlinear effects with equivalent-linear approach, by assuming literature variations of shear modulus and damping with strain.

2. Main shock recordings

The M_W 6.3 earthquake of 6 April 2009, hereafter called main shock, had a pure normal faulting mechanism, dipping at about 45° to the SW, with location at about 9 km of depth. Few days later, the aftershock activity migrated from the south-east of L'Aquila towards the NE at Arischia and Campotosto. The distribution of the aftershocks defined a complex, 40 km long and 10-12 km wide, NW trending extensional structure (Fig. 1).

The epicentral area of the main shock corresponds to the upper and middle Aterno river valley which is characterised by the high variability of the geologic and geomorphologic patterns. The valley is superimposed on a Quaternary lacustrine basin of tectonic origin (Fig. 2). The depth of the Quaternary deposits is variable, from about 60 m in the upper Aterno river valley to more than 200 m in the middle Aterno river valley. The 2009 seismic sequence was recorded by accelerometers of Rete Accelerometrica Nazionale (RAN) network, managed by the Italian Protezione Civile, some of which located at L'Aquila (AQK station) or in the NW of it (Fig. 2). They are equipped with three-component sensors set to 1 or 2 g full-scale, coupled with 24-bit digitizers. The permanent station AQU is operating since 1988 as part of the Mediterranean Network (MedNet), managed by the Italian Istituto Nazionale di Geofisica e Vulcanologia (INGV). AQU is equipped with a very broadband Streckeisen STS-1 sensor and Quanterra digitizer.

After the 2009 seismic sequence, geological and new interpretation of gravity studies have been performed at L'Aquila by Protezione Civile (2009) to reconstruct the shallow 200-300 m of subsoil. Based on these data, the stations turn out to be set on different geological

conditions. Stations AQG, AQA, AQV and AQM are located in the so called Coppito plain, a small graben filled of alluvial deposits. The stations AQM and AQG are installed on maiolica (whitish limestones) formation, whereas AQA and AQV are set on alluvial deposits with a thickness of 36 m and 46.5 m, respectively. The stations AQU and AQK are set on breccias (so called megabreccias), 80 m and 60 m thick, respectively, lying on alluvial deposits with thickness of 150 m and 250 m, respectively.
V_S models of the superficial 30 m of Aterno alluvial soils have been defined in the Coppito area (located in Fig. 2) (Costanzo et al., 2011) from the nonlinear inversion with Hedgehog method (Panza et al., 2007 and references therein) of the group velocity dispersion curves of the fundamental mode extracted with the FTAN method (e.g. Levshin et al., 1989; Nunziata, 2010). The models are characterized by an average velocity of 190 m/s.
Recordings of the main shock put in evidence the variability of the geological setting, with the maximum peak ground acceleration (PGA) of 0.6 g recorded at the AQV station (Fig. 3), and with high frequency content. Moreover, the recorded vertical accelerations, in some cases, are comparable or higher than the horizontal accelerations. Despite the high accelerations, low displacements (4-13 cm) are observed at periods higher than 1 s, with the exception of the AQK station, that shows displacements of 10 cm and 25 cm, in the vertical and horizontal components, respectively (Akinci et al., 2010). The high frequency content and the very short duration (2-5 s) of the ground motion, together with the building eigenperiods of 0.2-0.5 s, allowed fortunately to reduce the number of the collapses.
Spectral H/V ratios of the horizontal and vertical components evidence a strong variability, which prevents their use to recognize the resonance frequency of the station sites. The only exception is the station AQK (Fig. 4) that confirms the resonance frequency of 0.6 Hz obtained in the area by previous studies (De Luca et al., 2005). The crucial point is the definition of representative V_S profiles in the uppermost hundred metres, significant for the

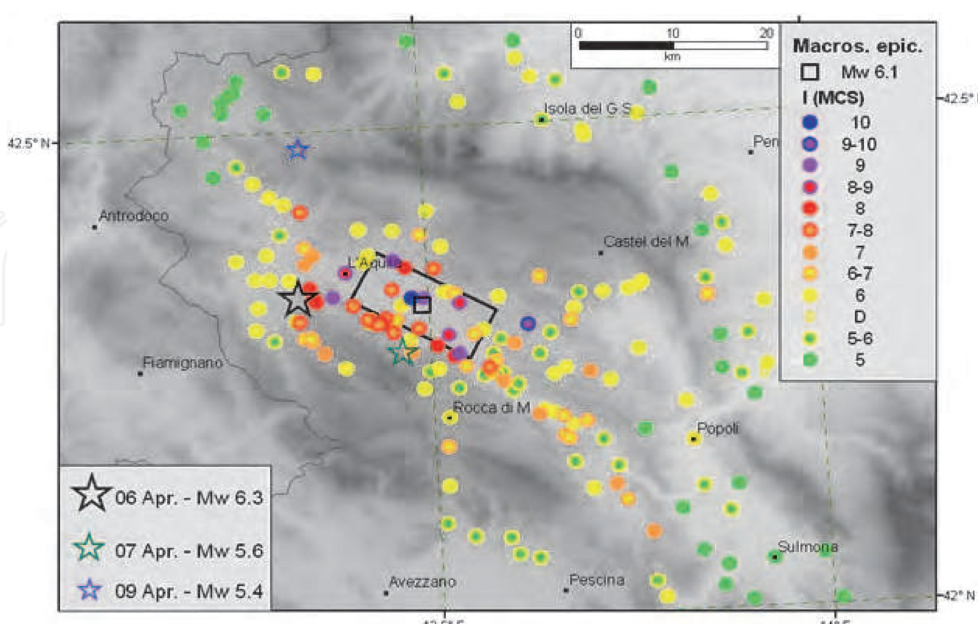


Fig. 1. Map of the effects of the 6 April 2009 earthquake and relative seismogenic box (from http://www.mi.ingv.it/eq/090406/quest.html)

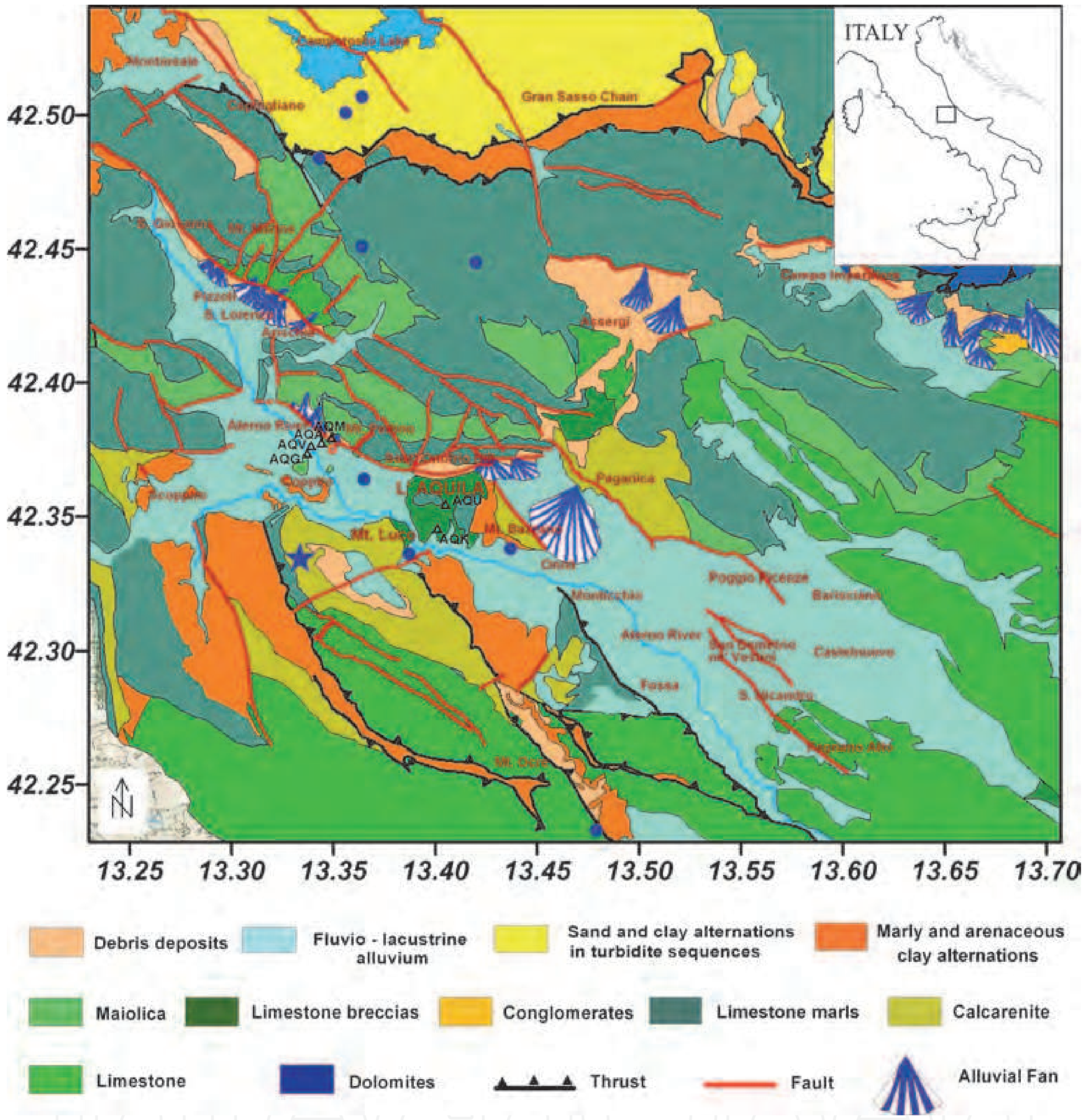


Fig. 2. Geological map of L'Aquila (modified from Vezzani and Ghisetti, 1998) with location of the RAN stations (black triangles), the main shock epicentre (blue star), the events in April 2009 (blue dots) and the site of the active seismic experiment (red square).

evaluation of site amplification effects. A good example is shown in Fig. 5 for the AQV station (located in Fig. 2) about the comparison of the frequency of the maximum peak of the H/V spectral ratio, relative to the main shock, with the 1D spectral amplifications, computed with SHAKE program (Schnabel et al., 1972), by assuming two different V_S data sets. The V_S profiles are relative to: 1. FTAN-Hedgehog analysis of surface measurements (Costanzo et al., 2011); 2. cross-hole measurements beneath the AQV station. Once more, such comparison evidences how 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).

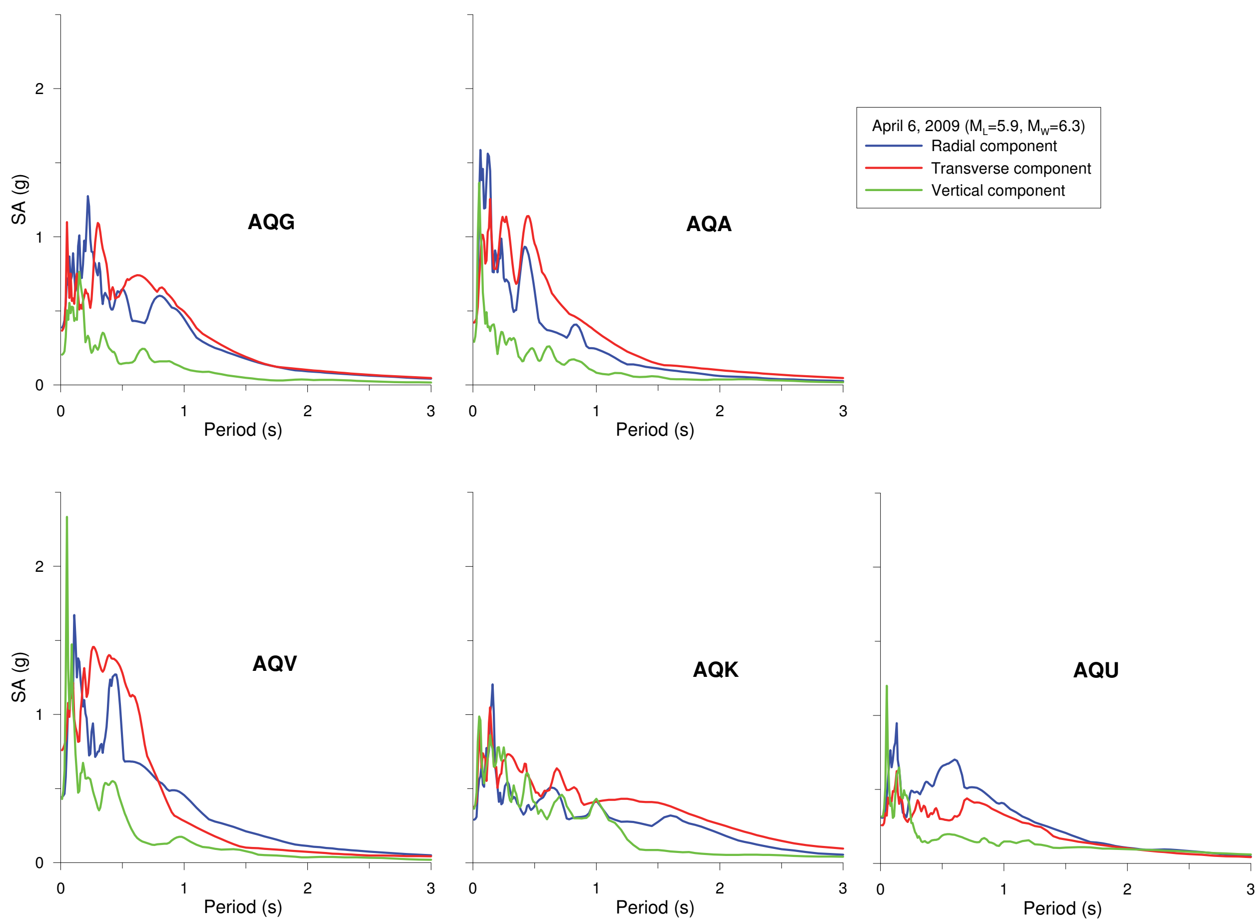


Fig. 3. Recorded acceleration response spectra of the main shock at the stations in the Aterno valley (located in Fig. 2)

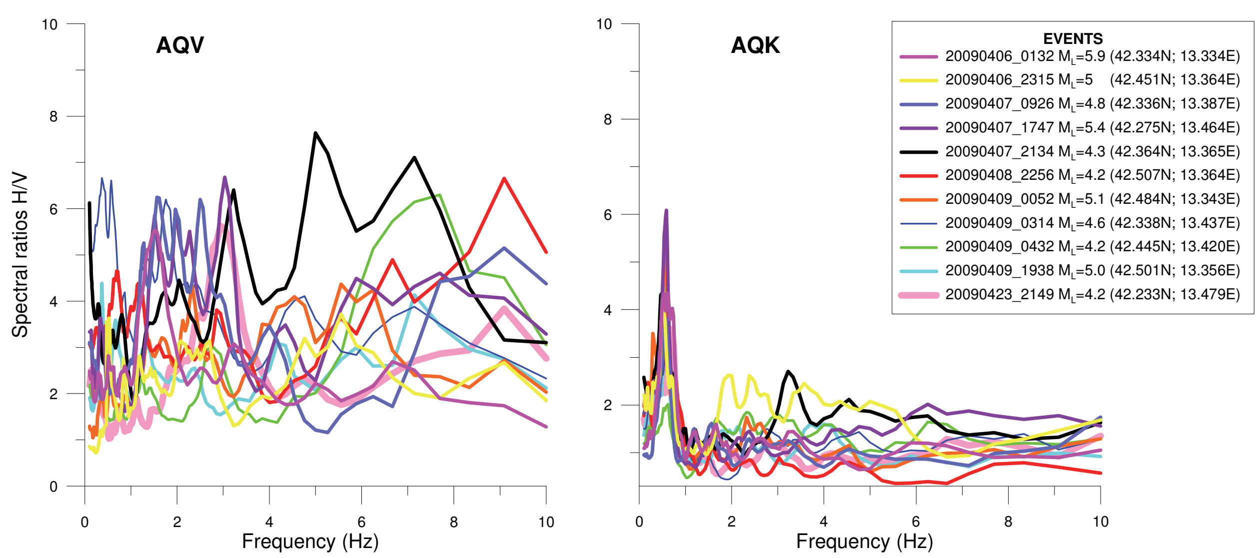


Fig. 4. Spectral ratios H/V relative to events recorded in April 2009 at AQV and AQK stations (located in Fig. 2).

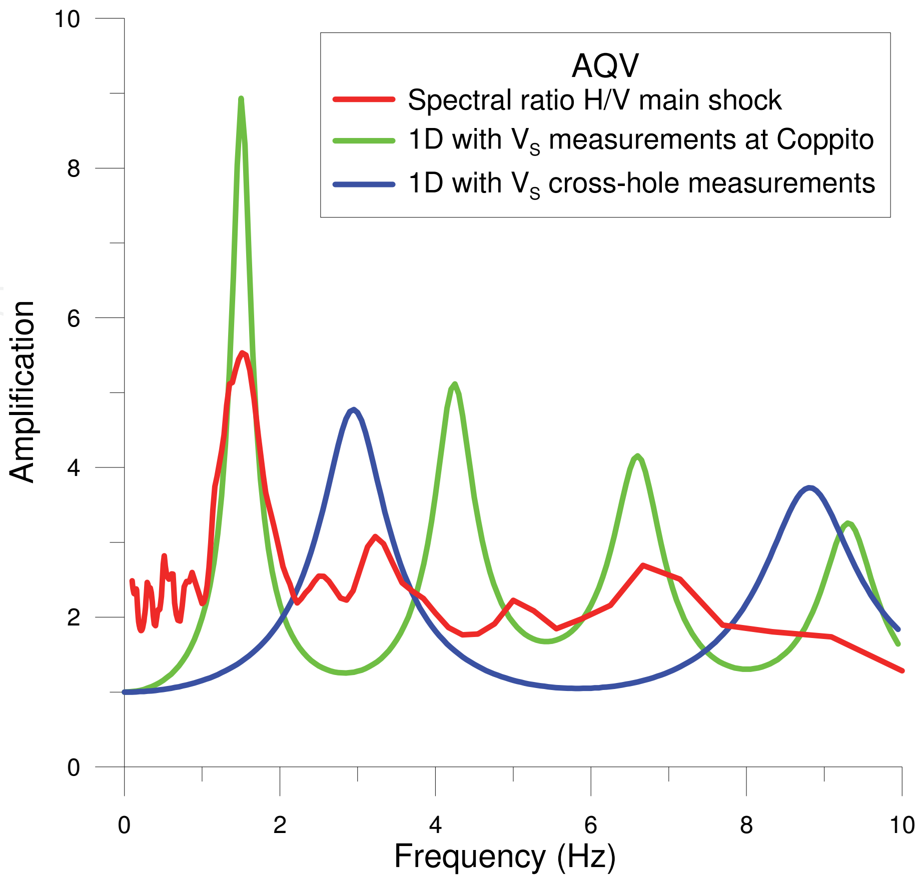


Fig. 5. Comparison between the resonance frequency estimated from the spectral ratio H/V of the main shock recorded at the AQV station and the 1D amplifications (SHAKE program) computed by assuming the V_S velocity profiles vs. depth measured by cross-hole measurements and obtained by FTAN-Hedgehog methods in the same lithotypes at Coppito (located in Fig. 2).

3. Ground motion modelling

Simulations of the 2009 L'Aquila earthquake have been performed with the NDSHA approach, using a hybrid method consisting of modal summation and finite difference methods (Panza et al., 2001 and references therein). This hybrid approach combines the advantages of both mode summation and finite difference technique. 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 (Fig. 6). 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). Two approximations have been considered to scale the seismogram to the desired scalar seismic moment: a scaled point-source approximation (Gusev, 1983 as reported in Aki, 1987), and an extended source approximation as proposed by Gusev and

Pavlov (2006) and Gusev (2011) and used by Gusev et al. (2008) for the modelling of Messina 1908 earthquake, where the rupturing process is modelled also in its random part.

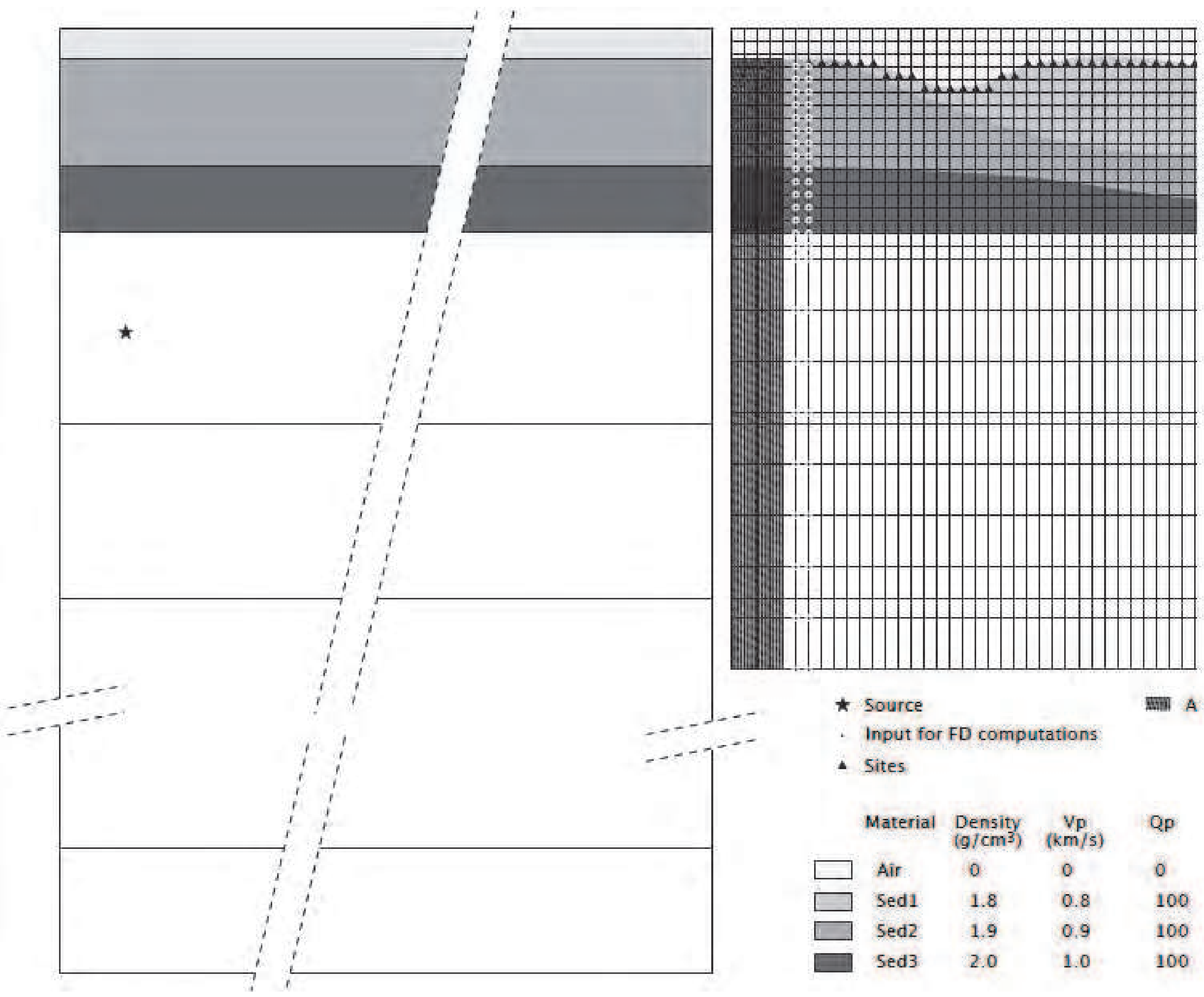
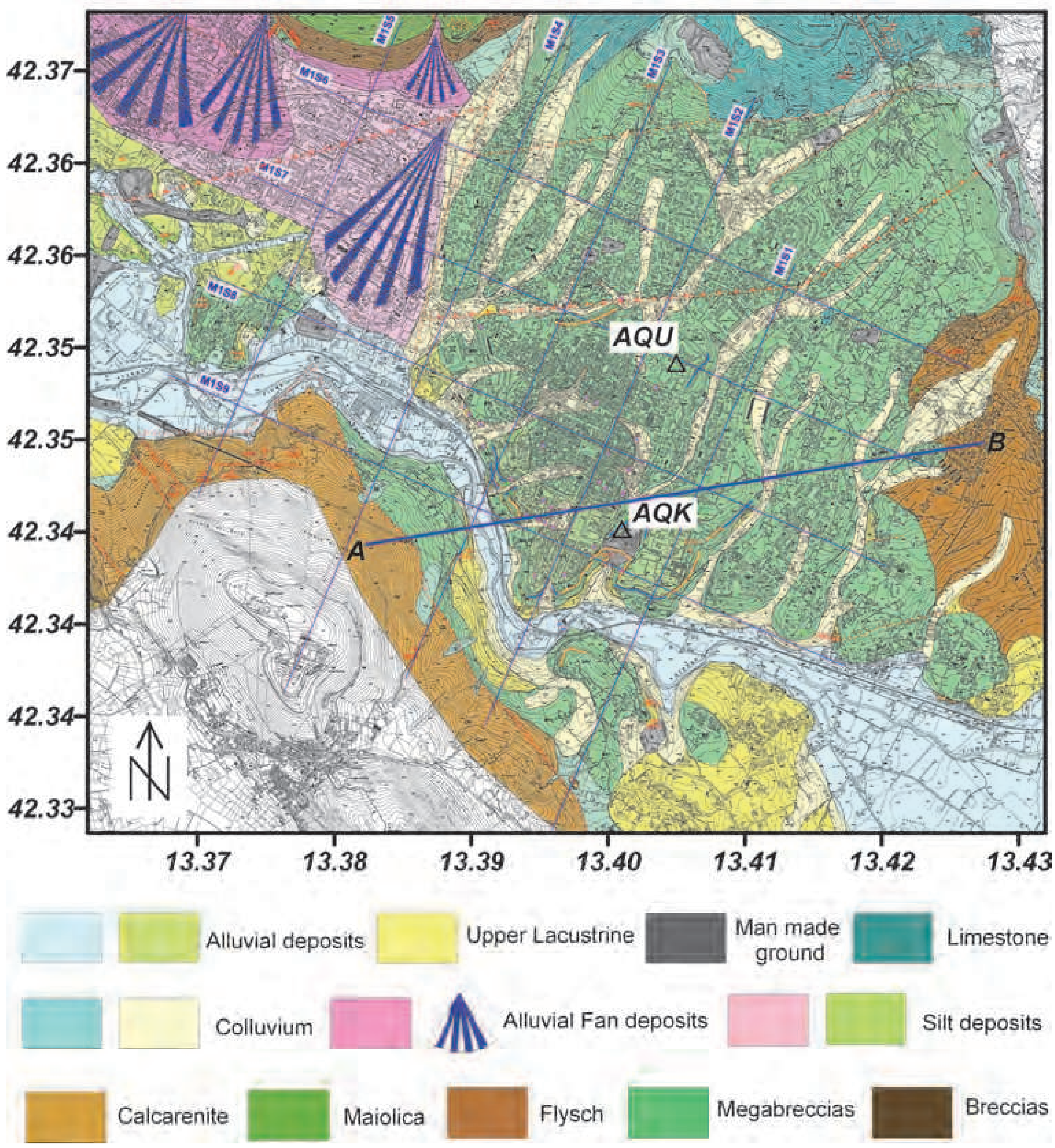


Fig. 6. Schematic representation of the hybrid method.

Modelling of the 6 April 2009 has been done along a SW-NE geological cross section at L'Aquila, close to the AQK station, and transverse to the Aterno river valley (Fig. 7a). 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. Physical parameters of the lithotypes (Fig. 7b, Tab. 1) have been attributed on available data (De Luca et al., 2005). The geological subsoil beneath the AQV station is similar to that below the receiver R19. Such assumption is validated by the good agreement between synthetic and recorded accelerograms both at the AQV and AQK stations, despite the lack of detailed geological and seismic knowledge along the cross section (Fig. 8). Then, a parametric study of the expected ground motion has been done along the cross section by assuming extended and point sources.

Spectral amplifications of about 10 are computed in correspondence of the Aterno river alluvial sediments (Fig. 9) and for a wide frequency range (2-5 Hz), corresponding to resonance frequencies of several structure typologies. This result is very different from the maximum peaks of H/V spectral ratios at 0.6 Hz computed from strong and weak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AQU
AQK
A
B
N
Alluvial deposits
Upper Lacustrine
Man made ground
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Colluvium
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Silt deposits
Calcarenite
Maiolica
Flysch
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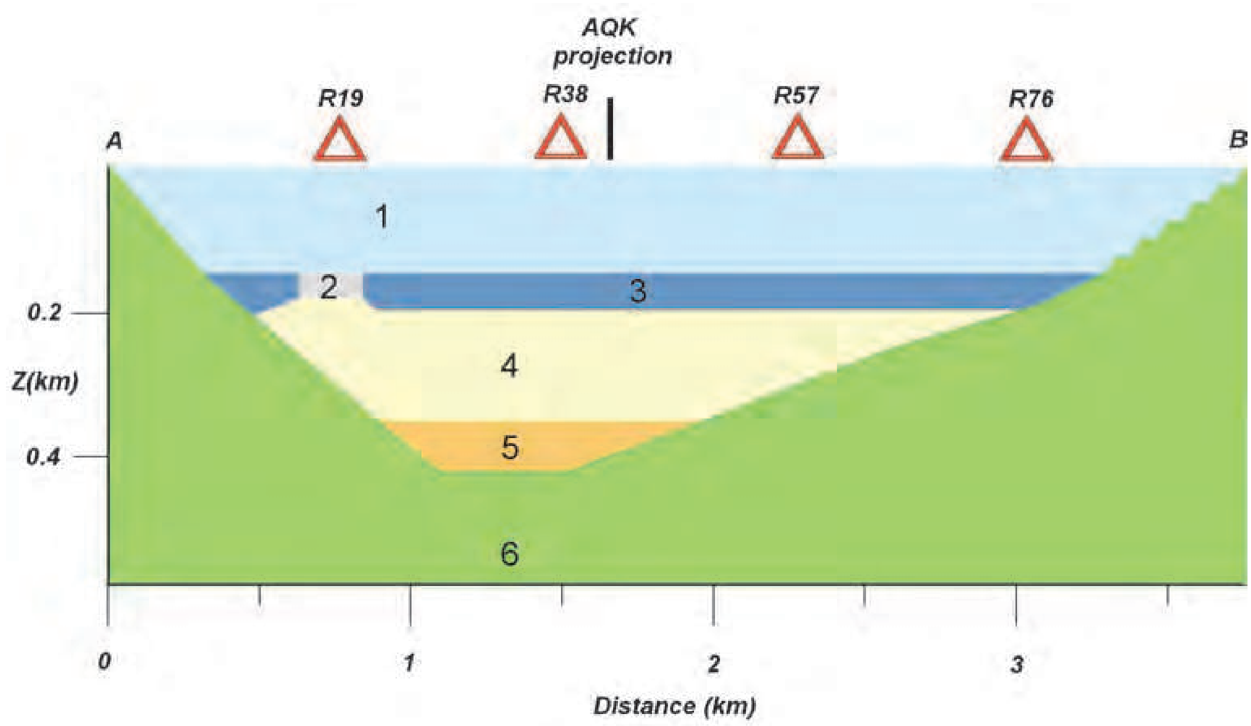
(a)



(b)

Fig. 7. (a) Location of the SW-NE cross section of the L'Aquila basin on the geological map 1:6000 (Protezione Civile, 2009); (b) computing cross section (from De Luca et al., 2005). Legend: 1. Air; 2. Aterno river recent deposits; 3. Megabreccias; 4. Upper lacustrine clays; 5. lower lacustrine clays; 6. Limestone. The physical parameters are reported in Tab. 1.

Name	Density (g/cm³)	V_P (km/s)	V_S (km/s)	Q_P	Q_S
Aterno Deposits	1.40	0.43	0.25	110	50
Megabreccias	2.00	1.56	0.90	220	100
Upper Lacustrine	1.80	0.86	0.50	220	100
Lower Lacustrine	1.80	1.12	0.65	220	100
Limestone	2.45	4.30	2.50	220	100

Table 1. Physical parameters of lithotypes

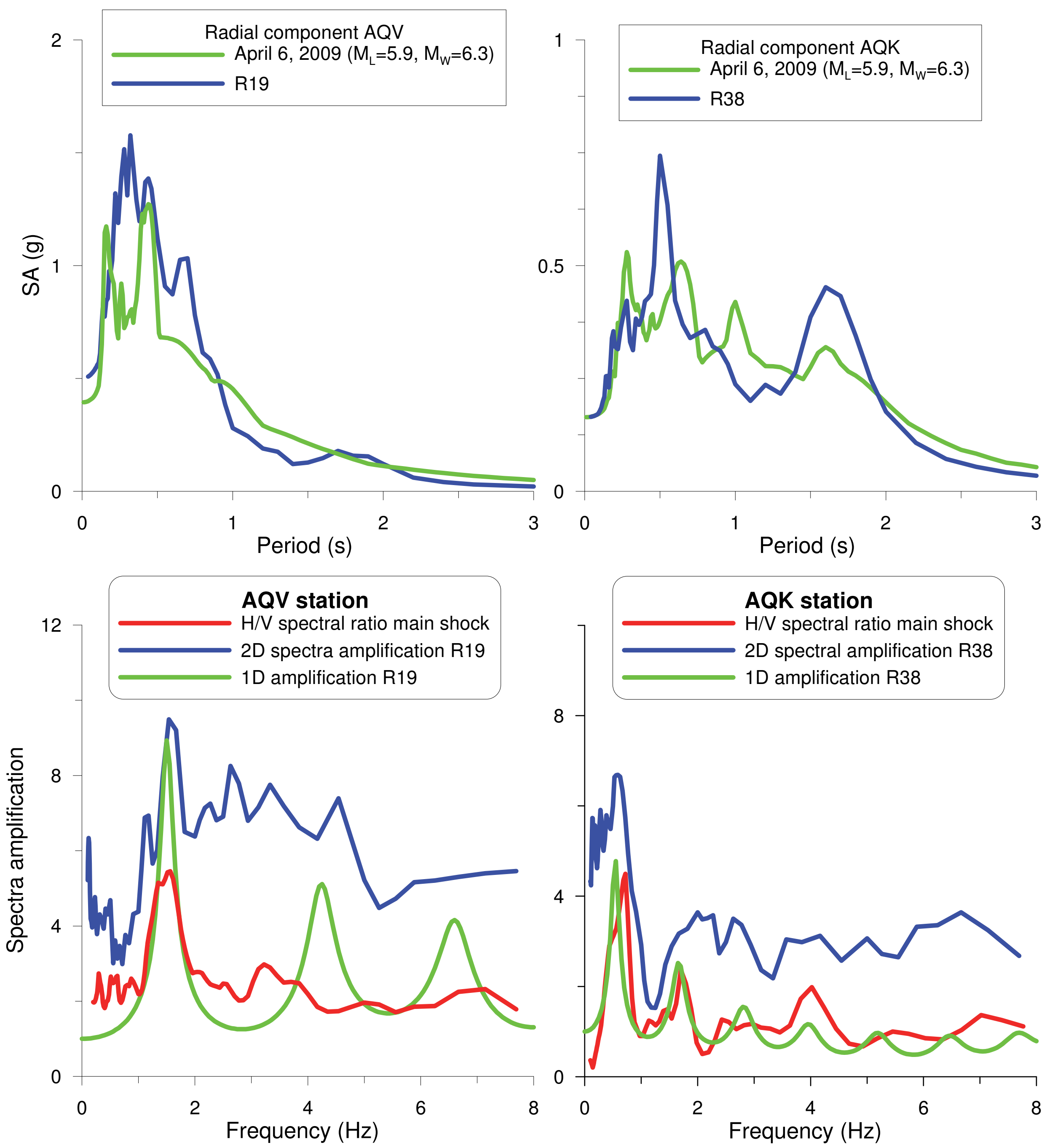


Fig. 8. Comparison at AQV and AQK stations of the: (top) recorded response spectra of the main shock with those computed at representative receivers R19 and R38, respectively (located in Fig. 7b); (bottom) recorded H/V spectral ratio with 2D and 1D (SHAKE program) spectral amplifications computed at receivers R19 and R38

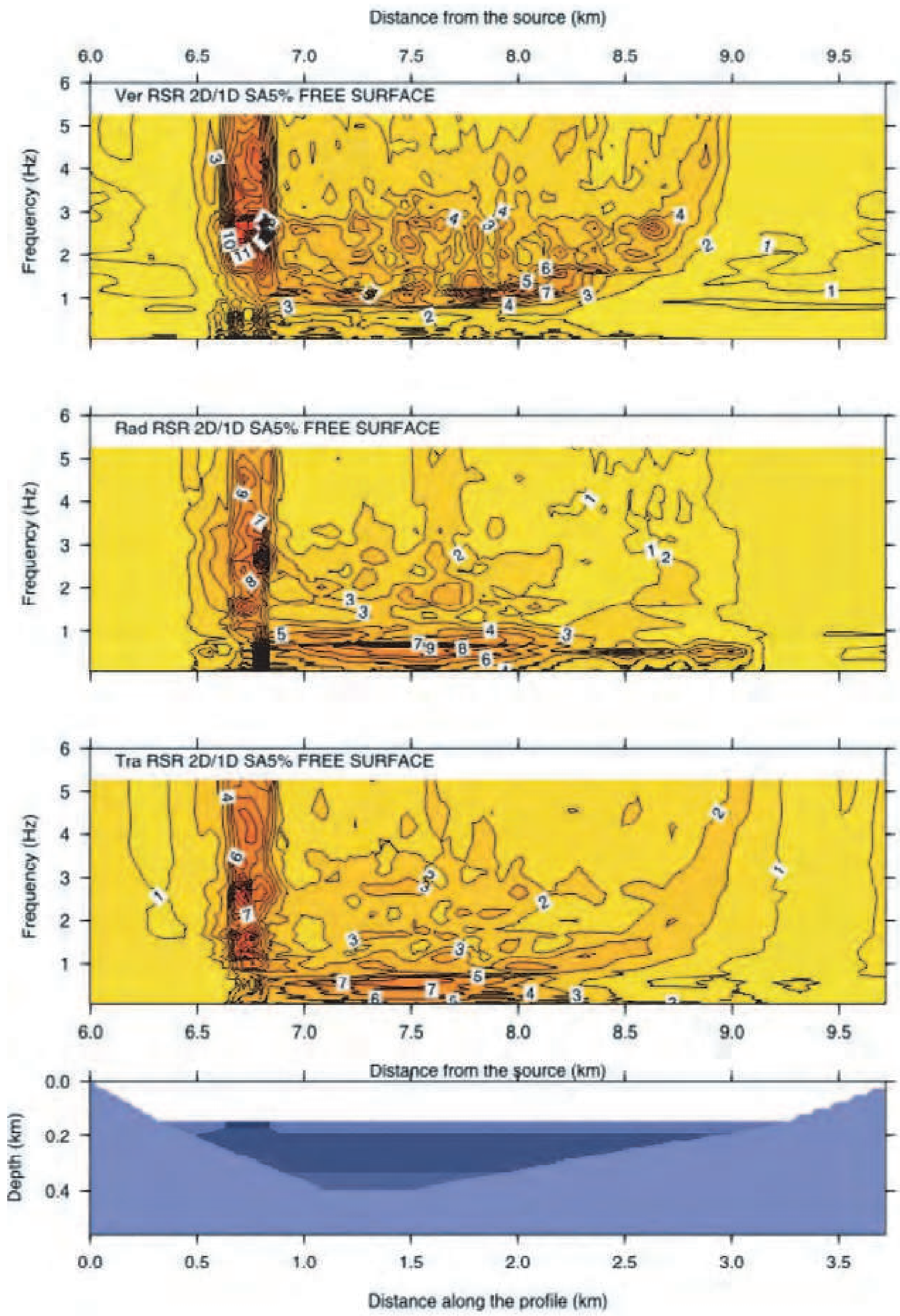


Fig. 9. Spectral amplifications (RSR 2D/1D) along the cross section of the L'Aquila basin. Response spectra are computed for 5% damping. From the top vertical, radial and transverse components of the computed ground motion.

earthquakes and noise along the same cross section (De Luca et al., 2005). The inadequacy of H/V spectral ratios is clearly seen even when they are computed from the same signals (synthetic) (Fig. 10). They do not show the strong amplifications where strong lateral heterogeneities are present. This result suggests great caution in the use of H/V ratios for seismic microzoning.

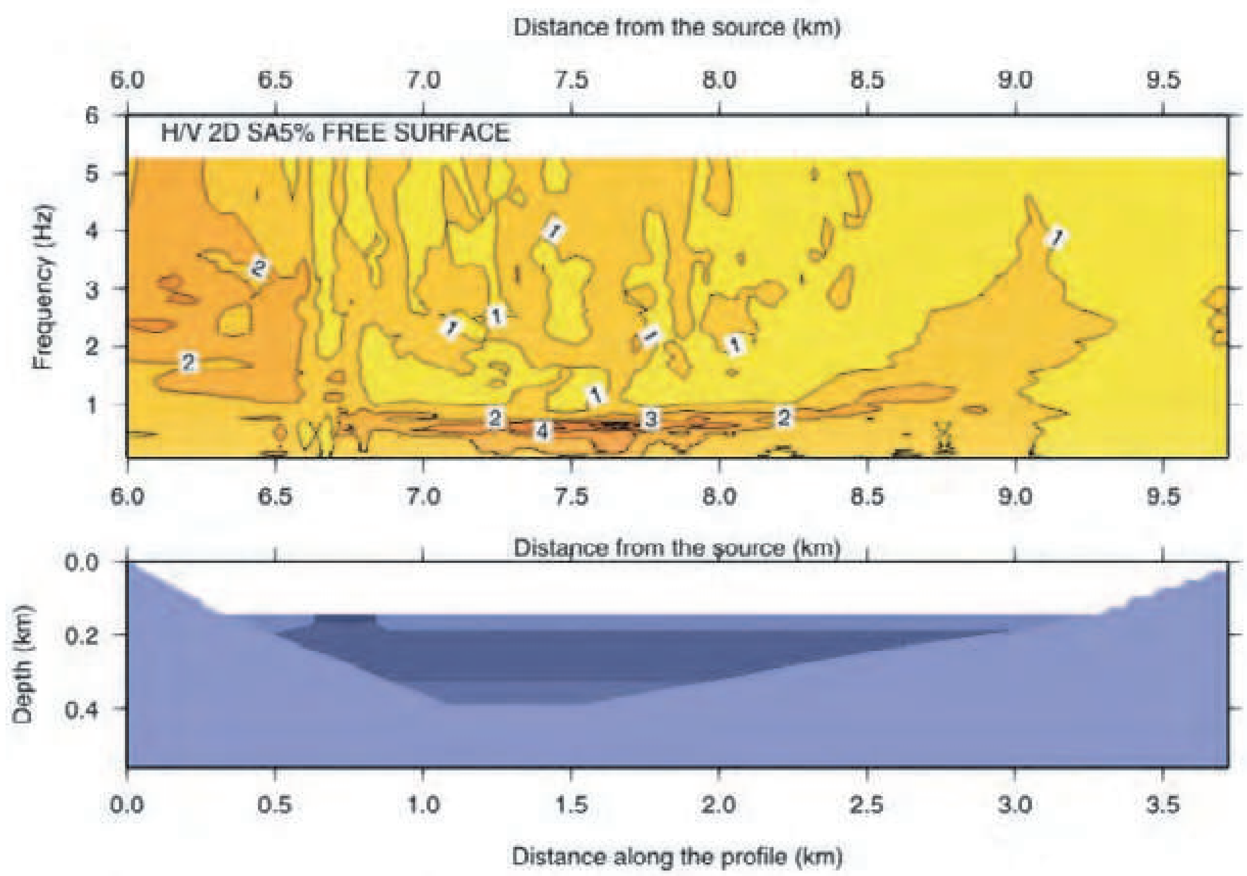


Fig. 10. Spectral amplifications along the cross section obtained from H/V spectral ratios computed on the same seismograms used for the 2D/1D amplifications shown in Fig. 9.

In November 2009, a map of buildings habitability at the historical center of L'Aquila, called red zone, has been published (L'Aquila Common Ordinance) (Fig. 11). It is evident that the majority of the buildings suffered serious damage (grade E). The cross section is representative of the historical center and, taking into account that generally 2-5 floor buildings are present, we can argue that spectral amplifications might have been responsible for damage, beside the near-field conditions.

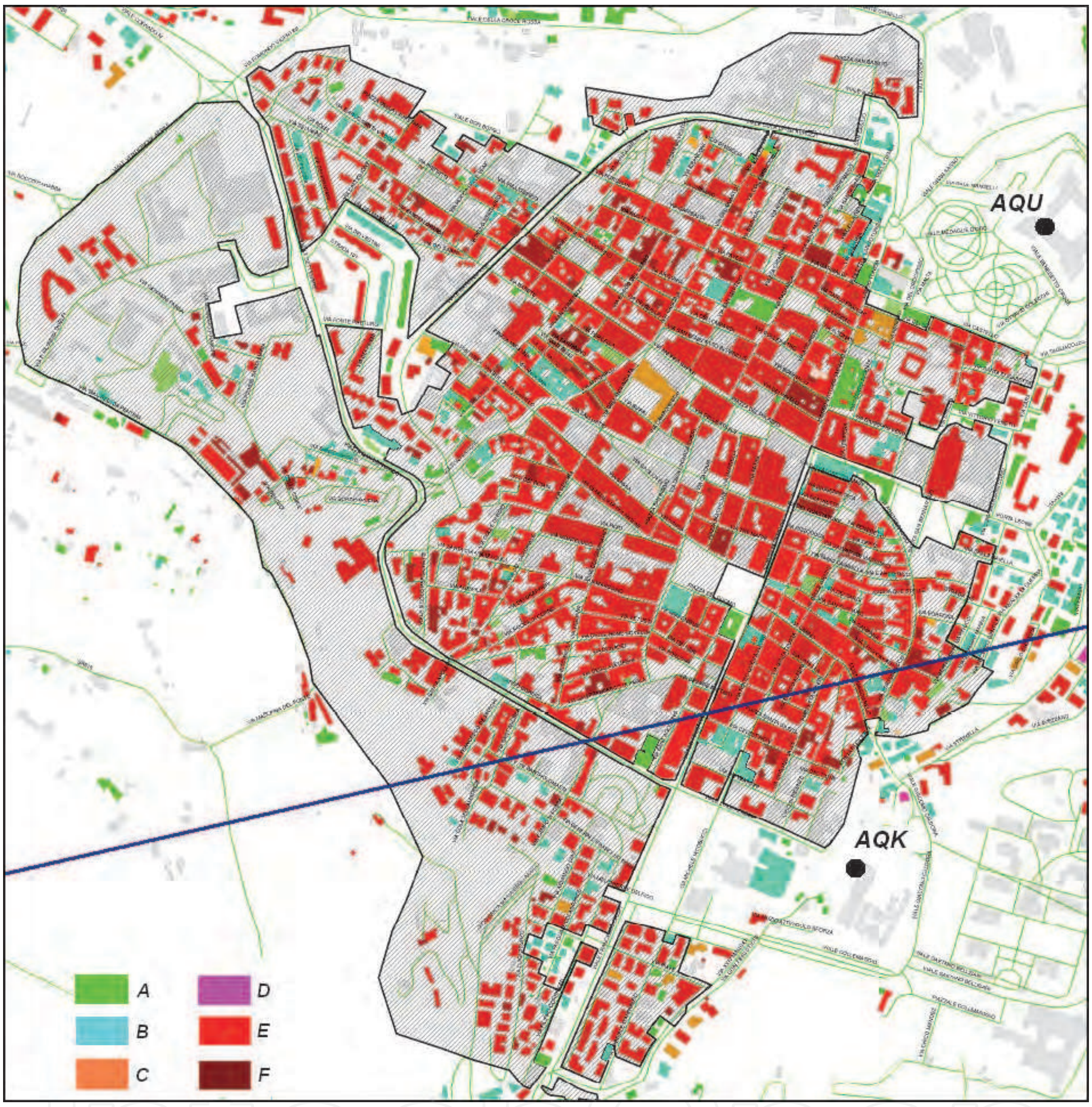


Fig. 11. Map of building habitability (decreasing from F to A) at L'Aquila red zone (Common Ordinance, 2009).

4. Nonlinear effects

Nonlinear site effects, such as increase in damping and reduction in shear wave velocity as input strength increases, are commonly observed in the dynamic loading of soils using geotechnical models, especially at shear strains larger than 10^{-5} to 10^{-4}.
Typical test data were published by Idriss and Seed (1968) and have been extensively used in soil engineering since that time. The amplification function at a site is controlled by the wave velocity and damping in the soil layer hence nonlinear site effects can be expected in strong-motion seismology. Amplification function becoming amplitude dependent (difference between weak and strong motions) is an indication of nonlinearity (e.g. Beresnev and Wen, 1996).

Evidence of nonlinear behaviour has been reported beyond a threshold acceleration from 0.1 g to 0.2 g. Nonlinearity is considerable in cohesionless soil but may be negligible in stiff soils.

Explicit evidence of strong-motion deamplification, accompanied by shifts of resonant frequencies towards lower frequencies, is found in a number of events throughout the world. Field et al. (1997) reported that ground-motion amplification due to sediments for the main shock of the 1994 Northridge earthquake was up to a factor of two less than the amplification observed for its aftershocks. More recently Molchan et al. (2011) supplied a list of hot/cold spots, in the definition of Olsen (2000), sites identified in the Italian macroseismic data, which are related to local fault geometry rather than to soil conditions.

Direct seismological evidence of nonlinear site effects was reported using spectral ratio techniques for two-station pairs, including soil-to-rock and surface-to-borehole station pairs. An intriguing result was published by Archuleta *et al.* (1992). At the Garner Valley downhole array, one of the accelerometers was installed at the surface and one was located at a depth of 220 m in granite. Two earthquakes with nearly coincident hypocenters but different local magnitudes were recorded, and amplifications were computed from spectral ratios at 0 to 220 m. It resulted that weak-motion amplification was significantly larger than strong-motion amplification in a wide frequency band, from 3 Hz to 40 Hz and that the most pronounced resonance was slightly shifted toward lower frequencies.

Nonlinear soil responses have been also identified by the horizontal-to-vertical spectral ratio applied to weak and strong motion records (Wen et al., 2006).

An estimate of possible nonlinear site effects, when experimental data are not available, can be obtained through a parametric study of response spectra dependence on shear moduli variations with increasing shear strain. Strain-dependent soil properties can be incorporated in dynamic response analysis by using an equivalent-linear approach as proposed by Idriss and Seed (1968). The approach is based on the assumption that the nonlinear soil response can be simulated by a linear elastic model with damping, provided that its constants are assigned according to the average strain level achieved, which is typically taken to be 0.65 times the maximum strain. The equivalent-linear method was implemented in the program SHAKE (Schnabel *et al.,* 1972), which has become a common tool for the routine estimation of dynamic ground response in geotechnical applications.

4.1 Nonlinear effects at L'Aquila

Among the aftershocks recorded in April 2009, one event (7 April 2009) occurred along approximately the same azimuth, at a comparable epicentral distance of the main shock, but with smaller magnitude (M_L=4.8) (Fig. 2). Nonlinear site effects can be observed at the AQV station from the comparison of the H/V spectral ratios relative to the main shock and this last event (Fig. 12). A small reduction of the amplitude and a little shift of the main peak of the H/V ratio toward lower frequency can be observed at the AQV station, the only station set on alluvial soils recording the smaller size event too. Instead, such nonlinear effect is not observed at the AQK station, set on megabreccias.

Nonlinear site effects are estimated at the two receivers (R19 and R38 in Fig. 7b) representative of the L'Aquila basin, with (like AQV station) and without (like AQK station) Aterno river deposits. SHAKE program is used to compute seismograms on the top of the soil columns (limestone is assumed as bedrock), using as seismic input the 1D seismogram computed, at the specific receiver, with the modal summation technique, by assuming different sources, that is an extended source with unilateral rupture, an extended source with bilateral rupture, and a point source. In a further test the PGA of the point-source signal has been conventionally taken equal to 0.1 g.

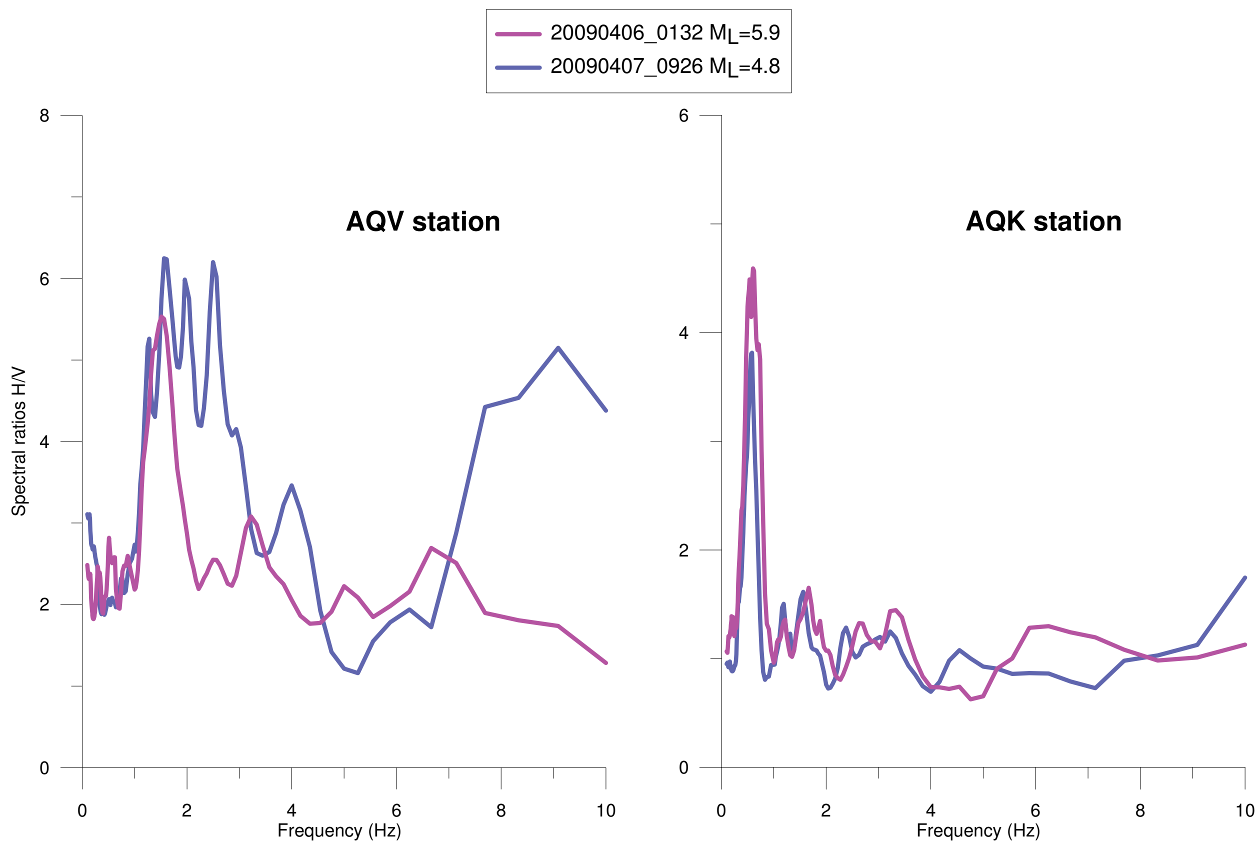


Fig. 12. H/V spectral ratios at AQV and AQK stations for two events with similar epicentral characteristics but different magnitude (location in Fig. 2).

Strain dependent shear modulus (G/Gmax) and damping (D/Dmin) of sand (pozzolana) (Guadagno et al., 1992), clay (CNR- GNDT, 2000) and peat (Vinale, 1988) are assigned, as plausible, to the Aterno river recent deposits, and of sand (pozzolana) to megabreccias and the lacustrine deposits (Fig. 13). Pozzolana sample is a cemented sand (hydrothermal hardening process) and can be considered as a stiff soil.

First of all, a remarkable difference between SHAKE (1D) and 2D (NDSHA) spectra exists, as expected, because of the lateral variations in the subsoil (Fig. 14). Response spectra computed with SHAKE by using the sand (pozzolana) soil nonlinear properties show nonlinear site effects (amplitude reduction and frequency shift to lower frequencies) more evident at receiver R19 and mostly for a point source (PGA=0.2 g). When considering PGA equal to 0.1 g and point source seismograms, such nonlinear effects turn out strongly reduced (Fig. 14 a-d).

A parametric study is performed at receiver R19 by assuming the seismic input corresponding to the point source and by attributing to the recent deposits of Aterno river the nonlinear soil properties of clay and peat (Fig. 15). A noticeable nonlinear effect appears

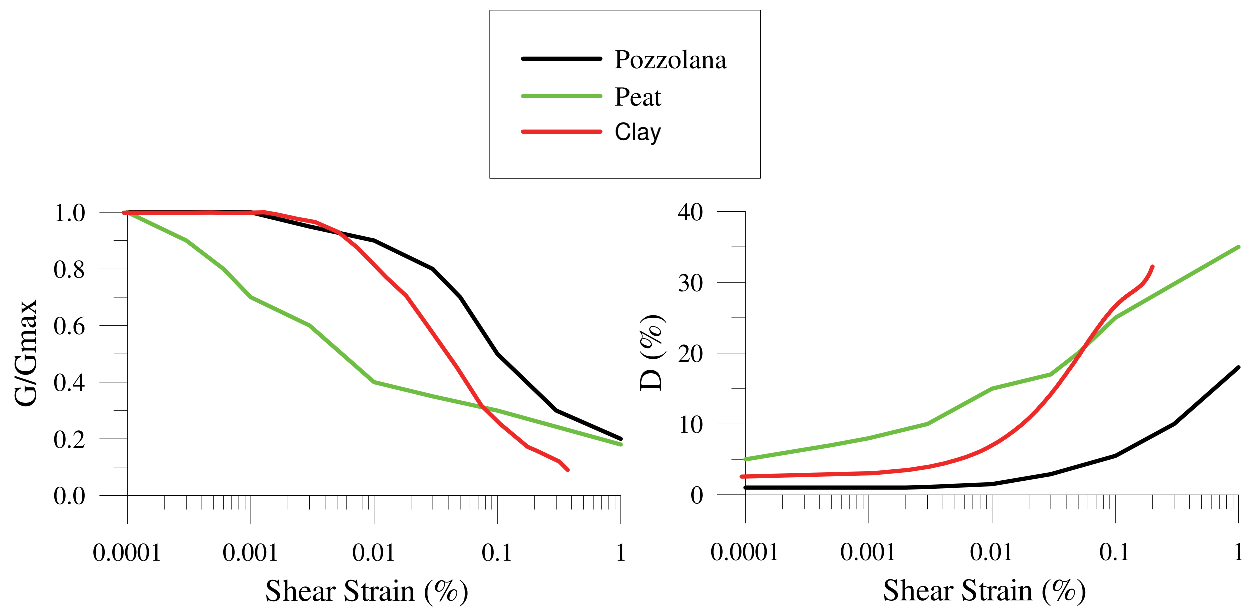
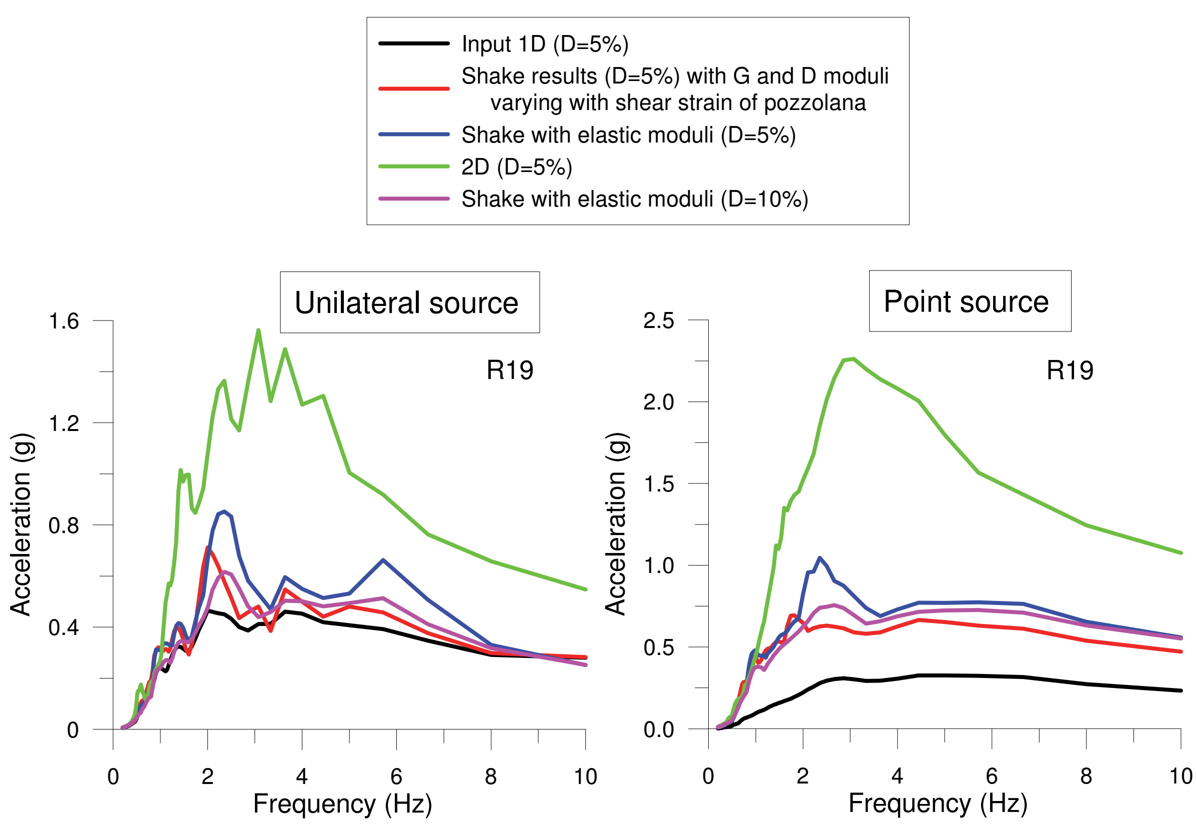


Fig. 13. Variation of shear modulus and damping with strain: pozzolana (Guadagno et al., 1992); clay (CNR-GNDT, 2000); peat (Vinale, 1988).



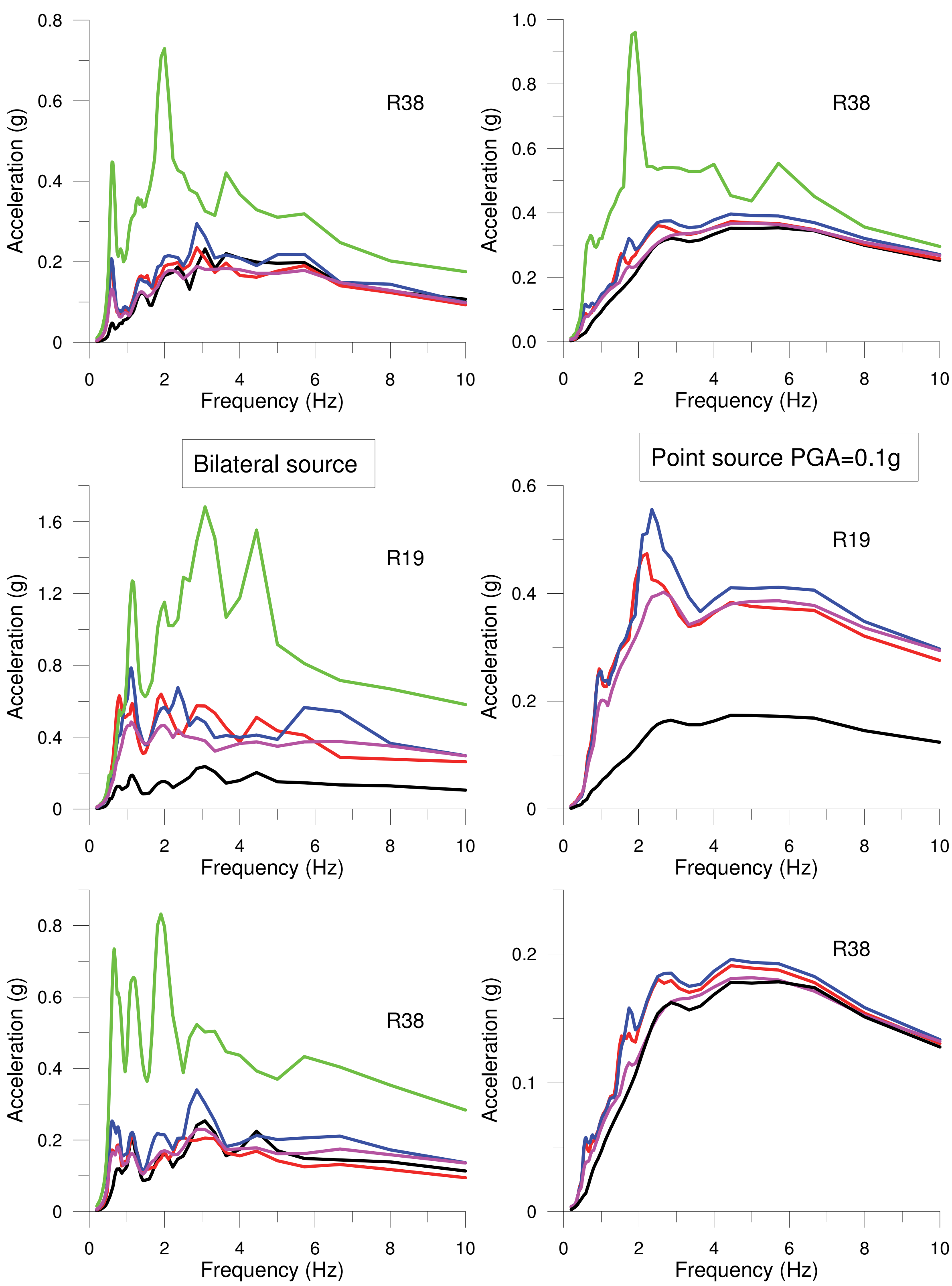


Fig. 14. Acceleration response spectra computed at R19 and R38 receivers with SHAKE program by using as input the seismograms computed, with mode summation technique, considering, from the left top: extended source with unilateral rupture; extended source with-bilateral rupture; point source. The fourth plot refers to the case in which the PGA of the point-source signal has been conventionally taken equal to 0.1 g.

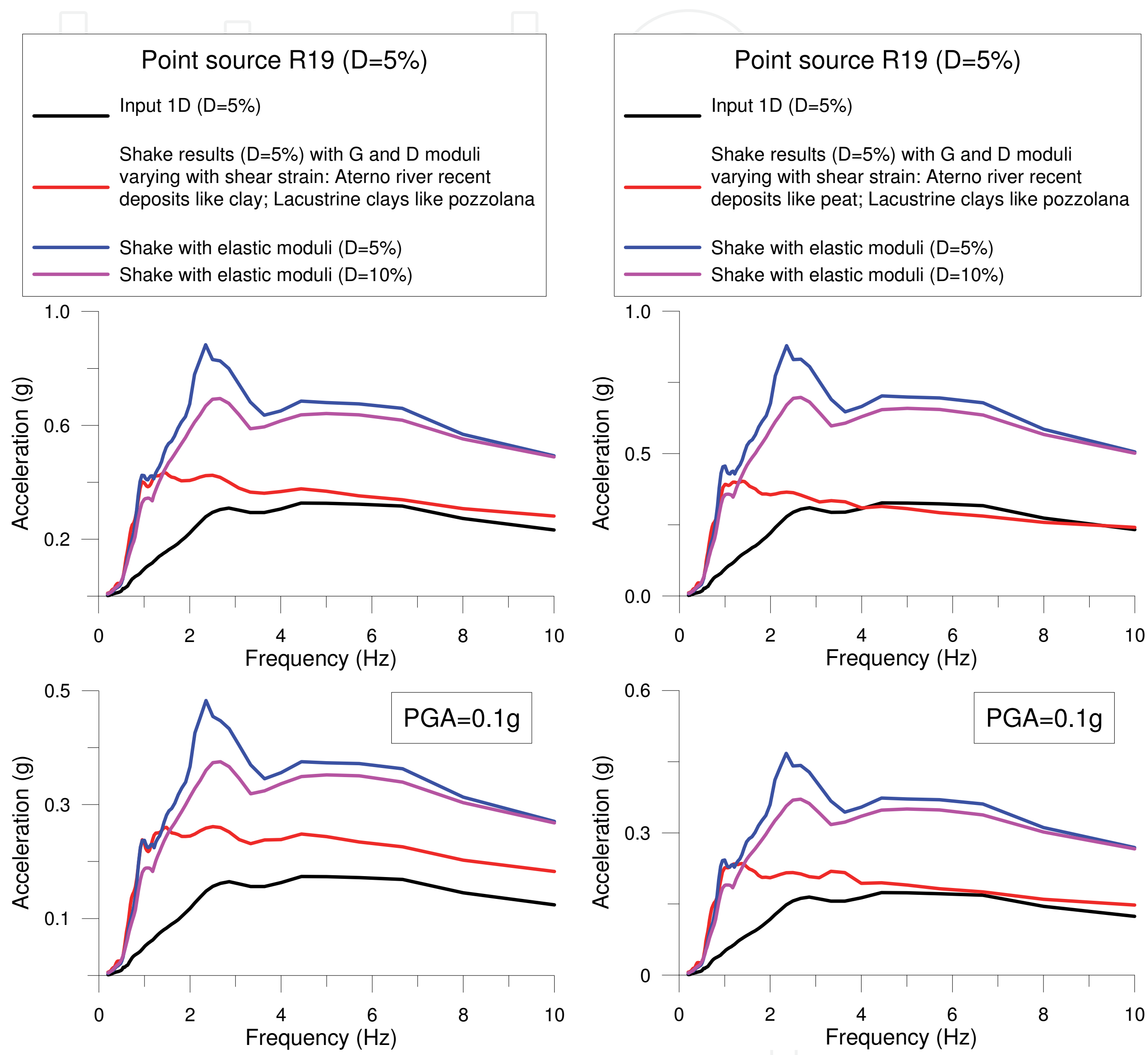


Fig. 15. Acceleration response spectra computed at R19 receiver with SHAKE program by using as input the seismograms computed with modal summation technique for the two point sources considered, by assigning to Aterno river deposits the strain-dependent dynamic parameters of clay and peat.

even in the point-source signal with PGA conventionally taken equal to 0.1 g. These results, though preliminary, as the real soil properties of L'Aquila basin are not known with sufficient detail, indicate that nonlinear effects may have locally affected the ground motion caused by the 6 April 2009 earthquake.

5. 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). The analysis of the H/V spectral ratios, both from recordings and computations, suggests that great caution must be paid in their use for reliable seismic microzoning. Another key point is the definition of V_S models representative of the seismic path, like those obtained from the nonlinear inversion of Rayleigh group velocities (Nunziata et al., 2004; Nunziata, 2007).

The simple parametric study of the variation of response spectra with the strain-dependent dynamic properties of soils, made using SHAKE, evidences that nonlinear effects may have affected the ground motion caused by the M_W 6.3 L'Aquila earthquake, as observed at the AQV station. Reduced spectral accelerations are due to (1) the amplitude dependent damping and (2) the shift of resonance frequencies towards lower frequencies due to the reduction of shear velocity. Nonlinearity under strong ground shaking depends on the physical properties of soils. Nonlinearity, that cannot be correctly simulated by the use of higher damping, may be considerable for soft clay and peat soils (PGA≥0.1 g) and negligible for stiffer materials for PGA ≥0.2g.

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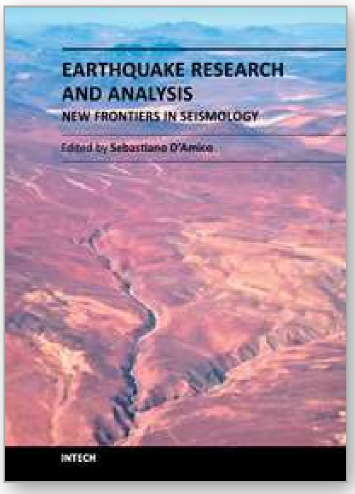

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The study of earthquakes combines science, technology and expertise in infrastructure and engineering in an effort to minimize human and material losses when their occurrence is inevitable. This book is devoted to various aspects of earthquake research and analysis, from theoretical advances to practical applications. Different sections are dedicated to ground motion studies and seismic site characterization, with regard to mitigation of the risk from earthquake and ensuring the safety of the buildings under earthquake loading. The ultimate goal of the book is to encourage discussions and future research to improve hazard assessments, dissemination of earthquake engineering data and, ultimately, the seismic provisions of building codes.