



4th IASPEI / IAEE International Symposium:

Effects of Surface Geology on Seismic Motion

August 23–26, 2011 • University of California Santa Barbara

THE ROLE OF LATERAL HETEROGENEITIES AND REVERSAL OF VELOCITY AT L'AQUILA (CENTRAL APPENNINES, ITALY) FROM A COMPARISON BETWEEN 2D MODELING AND OBSERVATIONS FROM THE 2009 EARTHQUAKES SEQUENCE

Paola BORDONI, Giuliano MILANA, John HAINES, Marco TALLINI, Francesco DEL MONACO

P. Bordoni

Istituto Nazionale di Geofisica e Vulcanologia, Centro Nazionale Terremoti, Murata 605, 00143 Rome, Italy
e-mail: paola.bordoni@ingv.it

G. Milana

Istituto Nazionale di Geofisica e Vulcanologia, Roma1, Via di Vigna, Murata 605, 00143 Rome, Italy

J. Haines

GNS Science, Dunedin, 764 Cumberland Street, Dunedin 9016, New Zealand

Marco Tallini

DISAT, L'Aquila University, L'Aquila, Italy

Francesco Del Monaco

DISAT, L'Aquila University, L'Aquila, Italy

ABSTRACT

The city of L'Aquila is built over a terraced alluvial basin filled by silt and silty-clay of lacustrine origin with average S-wave velocity of about 725 m/s, topped by a breccias unit (BrA) with V_s of about 900 m/s. Coupled with a reversal of velocity, there are marked lateral heterogeneities. In the southern area the stiff BrA unit laterally passages into softer deposits and is topped by red silt, i.e. LRCA, with an average velocity of 350 m/s. Bedrock is limestone and marls and its estimated maximum depth is of about 300-400 m. Recent geological and geophysical surveys performed during microzoning activities constrain this model.

Throughout the city measurements of horizontal ground motion (SSR and HVSNR) show a marked low frequency peak (< 1 Hz), with variable amplitude reaching its maximum in the southern area. However amplification level often exceeds two over the 2-10 Hz frequency range. Vertical ground motion has a remarkable peak at frequency higher than the horizontal one.

Bordoni et al. [2011] in their simulation work have shown that: 1) the velocity reversal filters out the high frequency content and 2) synthetic Rayleigh waves can predict the vertical ground motion amplification. Here we further our investigations on 2D ground motion focusing on the behavior of lateral heterogeneity in the BrA layer coupled to reversal of velocity. Synthetic spectral ratios from 0° and 90° incidence angle from SH waves are compared to observations from sites investigated by the microzoning portable network.

Keywords:

2D modeling, SH, spectral ratios, L'Aquila, site effects, reversal of velocity, lateral heterogeneity

INTRODUCTION AND MODEL DESCRIPTION

Experimental and modeling approaches fulfill complementary needs in the assessment of the soil response to ground

motion. Geophysical measurements and geological mapping contribute to build a geological model which will have some pitfalls, due to measurement failures on one side and unavoidable use of interpretation on the other side. The more complex the stratigraphical setting becomes the more likely are the uncertainties in the model. Therefore the best way to test a model, with the aim of refining and improving it, is to run seismic wave propagation simulations and check whether they can predict independent measurements. We have pursued this approach at the city of L'Aquila, where following the normal faulting $M_w = 6.3$ April 6th 2009 earthquake a wealth of geologic, seismologic, and geotechnical studies have been developed including those for microzoning purposes.

The main shock initiated 2 km west of the city center at hypocentral depth of 9 km and the fault plane was directly below it. The fault plane solution was consistent with a NW trending normal-fault mechanism [www.bo.ingv.it/RCMT] matching the NW-SE striking extensional regime of the Central Apennines. The earthquake had a disastrous impact on the whole epicentral area resulting in high toll in human lives with 309 people killed. Most of the casualties occurred in the historic city center where several buildings collapsed including some recent reinforced concrete ones. Beside collapses, a big portion of public and residential buildings were declared unusable after a survey performed in the days following the event leaving sixty thousand homeless.

L'Aquila is in the Aterno River valley, a long NW-SE valley surrounded by mountain ranges, with the highest relief of the Apennines chain, the Gran Sasso range, to the NE. The downtown is built over a terraced alluvial basin (Fig. 1-2). The terrace is in contact with outcropping limestone to the north, while moving towards the south the terrace is superimposed on silt and silty-clay of lacustrine origin, LK, with average S-wave velocity of about 725 m/s, topped by a breccias unit, BrA, with attributed V_s of about 900 m/s. The thickness of the BrA formation ranges from tens of meters in the north to just a few meters in the southernmost part. The terrace surface gently dips to the SW, has some minor incisions filled by colluvial deposits and a major incision to where the Aterno river is flowing, of about 90 m depth at its lowest point below the terrace. On the opposite side of the asymmetrical valley the bedrock is marls. Coupled to the described superficial reversal of velocity, there are marked lateral heterogeneities due to the history of sedimentation. A new geological survey of the area [Gruppo di lavoro MS_AQ 2010] has recently highlighted that the BrA unit moving towards the SW along a NE-SW profile decreases its competence with the breccias being gradually substituted by gravels and sand in a delta-fan-like sorting manner. In addition, such deposition occurred for a while into a lake, while lately it has been subaerial with the formation of a fine residual deposit, the Limi Rossi del Colle dell'Aquila, LRCA, a red silt unit which tops the BrA unit (Fig. 1-2). The LRCA velocity-depth profile has been measured down-hole to 30 m (at S5) finding an average velocity of 350 m/s [Gruppo di lavoro MS_AQ 2010]. There is only one measurement of the depth to bedrock, which was reached at 190 m at the borehole S3 located in the Aterno River Valley [Amoroso et al. 2011]. Another 300 meters deep borehole drilled in the center of the city (S2) did not reach the bedrock. This is in agreement with gravimetry modeling that estimated a maximum depth in about 300-400 m [Amoroso et al. 2011].

In order to model the 2D behavior of the area, we have drawn two perpendicular cross-sections (Fig. 2) modifying the ones from Gruppo di lavoro MS_AQ [2010] to take into account the local geology in proximity to the seismographs of the portable network. The A-A' profile (top panel) has a NE-SW strike. We have modeled the lateral heterogeneity inside the top layer, BrA, using a horizontal velocity gradient, which gives rise to a variable impedance contrast between the top two layers, excluding LRCA, in the range of 1.2-0.7 (Table 1). The lateral passage at the same topographic level to the fine, slow and thin LRCA deposits has been modeled using another layer with a different but constant velocity. The B-B' profile (bottom panel) is a simple model with a surface reversal of velocity and has been chosen to study the depth to the bedrock along the NW-SE valley axis.

We have simulated the 2D responses along these profiles for propagating SH waves with 0° and 90° incidence angles. We have chosen these angles because previous studies [Bordoni et al. 2010, 2011] have found that the model responses for these incidences are the end-member cases for the full 0° to 90° range. We have computed synthetic spectral ratios and compared them to the experimental ones derived from averaging many aftershocks covering a wide range of azimuths and distances, which were recorded by the microzoning portable network [Milana et al. 2011].

Tables 1 and 2 list the mechanical properties of the soils and rocks used in the modeling. Note that in the AA' profile we have introduced a horizontal S-wave velocity gradient in the BrA layer. This decreases the speed from 900 m/s in the NNE part of the model end to 500 m/s at the SSW truncation of the layer, directly below the LRCA layer, which has a constant velocity of 350 m/s. Profile BB' has a vertical velocity gradient from 450 m/s to 650 m/s in the LVM

unit, a silty unit of fluvial origin. Profile BB' also has a marked artificial horizontal gradient for the attenuation quality factor in the BrA and LK layers added at the left-hand end of the model: this is a work-around option recognizing and compensating for the lack of basin pinch-out there that is required by the modeling algorithm.

The A-A' cross-section runs south-east of the cross-section modeled in Bordoni et al. [2011] along a similar strike (see Fig. 1). That study investigated the behavior of the velocity reversal in the top layer associated with the stiff Breccia de L'Aquila unit (BrA), using SH, P-SV and Rayleigh waves. The authors ran two different velocity-depth models for the same cross-section. The first model (SMTH) was topped by a stiff layer with about 2:1 impedance contrast with the underlying layer. In the second model (NORV) the top two layers were replaced with a single layer with the properties of the softer second layer. By having different properties in the top layer of the two models the effects of the heterogeneity in the near-surface geology were dealt with to first-order, focusing on the limits of the stiff BrA distribution. The NORV model more adequately describes the effect of the area close to the SW edge of the L'Aquila terrace, where BrA rocks give way to LRCA. The SMTH model, on the other hand, better describes the effect of the area where BrA rocks are at the top of the stratigraphy. The authors found that sites closer to the SW L'Aquila terrace edge were matched better by the NORV model, while sites clearly on BrA, were matched better by the SMTH model. Bordoni et al. [2011] found the major amplification effects to be in the 0.5–1.5 Hz range, in agreement to De Luca et al. [2005].

2D MODELING

The simulations have been performed using the impedance-operator-based numerical code described in Haines et al. [2004] and Hulme et al. [2004]. This code for laterally varying media is formulated in the frequency–wavenumber domain and has many characteristics in common with the reflectivity technique for laterally uniform media [Kennett 1983], including the reflectivity technique's inherent accuracy. For both models, we have simulated propagation for SH waves with vertical incidence (0°) and horizontal (90°), incidence, with the latter entering the models from their right-hand sides. The incident waveform is a plane S wave with a delta-like time function. Seismograms have been generated every 20 m giving 250 synthetics for AA model (Fig. 3 a-b bottom panels) and 275 for BB model (Fig. 4 a-b bottom panels). From these synthetics we have computed spectral ratios using as reference the synthetics at the basement site at the right-hand end of each model, corresponding to reference site AQ12 for profile AA' (Fig. 1). Synthetics spectral ratios interpolated along the strikes of the models are shown for 0° incidence angle (Fig. 3a and 4a top panel) and for the 90° incidence angle (Fig. 3b and 4b top panels). The low frequency peak is clear and also its dependence on basin thickness. It is also clear that for both incidence angles local waves are generated at diffracting points at the edge of the basin and at the sloping interfaces, and they travel back and forth interfering amongst themselves. The modeling also clearly shows that the soft LRCA deposits generate 'entrapped' high frequencies waves with high values of amplification being predicted.

COMPARING EARTHQUAKE AND 2D SYNTHETIC SPECTRAL RATIOS

Earthquake spectral ratios

We quickly summarize the main characteristic of the horizontal ground motion as seen by earthquakes [Milana et al. 2011]. Starting from the data presented in Milana et al. [2011], we have re-evaluated the standard spectral ratios (SSR) with the aim of reducing the standard deviations of the results, using a longer S-wave time windows and removing those events with poor signal-to-noise ratio. After data reprocessing the standard deviations are still high suggesting a dependence of SSR on distance and azimuth. Site AQ12 (Fig.1) is the reference site. At all sites there is a broad low frequency peak centered at about 0.7 Hz, which diminishes to levels near 1 at frequencies higher than 2 Hz. The only exceptions along profile AA' are sites AQ18 and AQ08 which show smaller amplitude at low frequency than other sites. The two horizontal components of earthquake spectral ratios at some sites are different (e.g. FAQ2 and NAPO) with the East-West component bigger than the North-South and factors reaching an average of 7. In the high frequency range some amplification is visible over the 2-10 Hz frequency band but without any clear sharp peak. The high frequency factors found at some sites (AQ08, SANT) may be related to very local features and are not easily modeled. Vertical ground motion (not shown) has a remarkable peak at higher frequency (1 Hz) than the horizontal peak.

AA' model: synthetics vs observed spectral ratio

In Fig. 5 we have compared 2D synthetics spectral ratios from SH waves with vertical and horizontal incidence angles to earthquakes horizontal spectral ratios computed using AQ12 site as reference.

Vertical Incident SH waves: At sites AQ08 and AQ07 and AQ03, NAPO, AQ01 (that is sites at both ends of the modeled basin) the synthetics spectral ratios frequency peak is at 0.7 Hz matching the earthquake spectral ratios. At all the other sites (AQ02, FAQ1, PAOL, FAQ2) over the deeper area of the basin the simulations predict a 0.5 Hz peak in contrast to the 0.7 Hz peak of the data. The amplification level at low frequency predicted by the 0° incidence simulation is typically less than the data average but is within one standard deviation at all sites, except AQ18. At the SW end of the model, where the earthquake amplification factor at 0.7 Hz reaches its maximum (NAPO), the amplitudes of the synthetic spectral ratios are substantially less than the data averages and roughly equal to the lower one standard deviation bounds. We have modeled the 1D response (not shown) at sites PAOL and FAQ2 for vertical incidence and obtained the same peak at 0.5 Hz with amplification factor very similar to the 2D one. It is interesting to note that for some sites (AQ02, FAQ2, AQ07) there are remarkable differences between the two incidence angles.

Horizontal Incident SH waves: At sites PAOL to AQ03 synthetics spectral ratios match the 0.7 Hz frequency of the peak, while at sites AQ08 to FAQ1 the frequency of the predicted peak is slightly too low. The amplification level of synthetics spectral ratios match the average of observations at site PAOL, FAQ2 and NAPO, is of the same size as the lower one standard deviation bound at sites AQ01 AQ03, is of the same size as the upper one standard deviation bound at AQ02 and FAQ1, and overestimate the data at AQ08. In general the horizontal incidence waves perform better in fitting the frequency peak and amplitude of the data at all sites, except AQ18.

To summarize 1D and 2D vertical incidence on one hand can explain some features of the NE sites but they fail to reproduce the main features of the middle and SW sites. The 2D horizontal incidence on the other hand predicts the low frequency effect at sites PAOL and FAQ2, in the middle of the profile, in terms of frequency peak and amplification level, but fails to reproduce the peak amplification values at sites closer to the terrace edges AQ01, NAPO, AQ03.

At high frequency > 3Hz the 2D synthetics spectral ratios for both incidence angles predict high amplification factors matching the amplification level of the NE sites but overestimating the response of the SW sites. The SW sites are on the slow LRCA unit, however their predicted high amplification factors are not seen in the data. These 2D factors are always higher than those produced by 1D simulation for vertical incidence though the peaks predicted are very similar.

BB' model: synthetics vs observed spectral ratio

Synthetic spectral ratios (Fig. 6) at sites AQ20 and AQ14, at the ESE end of model BB, have no similarity at low frequencies to earthquake spectral ratios but there is a match for the high frequency peaks. At sites VINC, AQ05, AQ06 and FAQ5 the low frequency peak of the data is matched by both incidence angles. At the SANT site the peak frequency of the low frequency amplification peak that the model predicts is too high. At high frequency there is general match between synthetics and earthquake spectral ratios, except at AQ05 where the 90° spectral ratios overestimate the amplification factor from data especially between 3-5 Hz.

CONCLUSION

We have modeled the response of two 2D cross sections to SH wave incidence at 0° and 90° and compared their synthetics spectral ratios to the earthquakes spectral ratios with the eventual aim of refining and improving the geological model. The geological feature that characterizes the AA' model is lateral velocity variation inside the BrA layer which in some sectors give rise to inversion of velocity with the underlying LK layer. The B-B' profile is a

simple model with the near-surface reversal of velocity laterally uniform and has been chosen to study the depth to the bedrock along the NW-SE valley axis.

- 1) For both geological cross-sections the 2D modeling can account for the main characteristics of the amplification at low frequency at most of the sites, though the high frequency features have to be improved and understood further. The agreement at low frequency is particularly good with horizontal propagation. Some mismatch still exists at the ends of both models, suggesting revision of the geological model is required, especially for profile BB' at its ESE edge.
- 2) The characterization of the S-wave velocity of the LRCA unit must be improved since the simulations predict frequency characteristics of the amplification factors not seen in the data. One of the reasons of this mismatch might be extreme heterogeneity of this deposit, inconsistent with it being a constant velocity layer (both laterally and vertically), and the heterogeneous properties would not be reliably characterized using drilling at a single site, which is all that is available at present. In other words, more geotechnical data is required.
- 3) The high variability of the horizontal spectral ratios at sites along the cross-sections is reproduced at most sites using waves propagating at 0° and 90° incidence angles. At sites closer to the south-end of the l'Aquila terrace, along the AA' profile, 2D modelling is not sufficient to account for all the variability and energy shown by data, suggesting that some of this variability may be due to 3D effects.

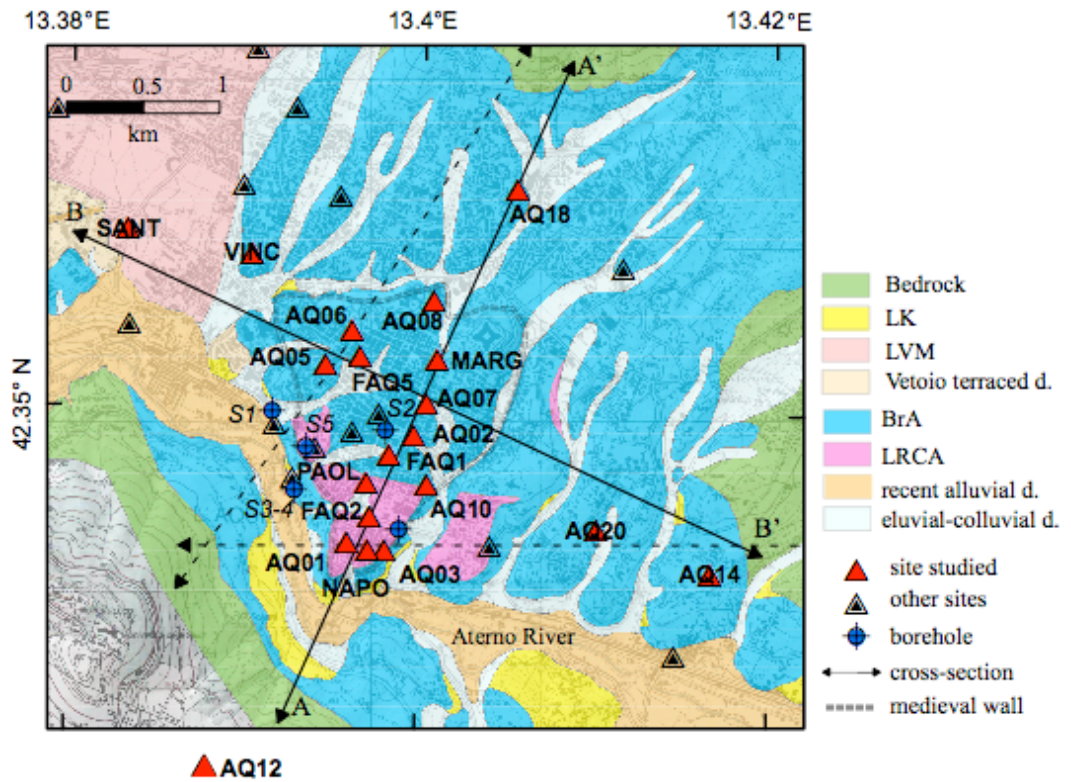


Fig. 1. Geological map including location of seismographs, boreholes and cross sections modeled in this paper and in previous paper (dashed line)

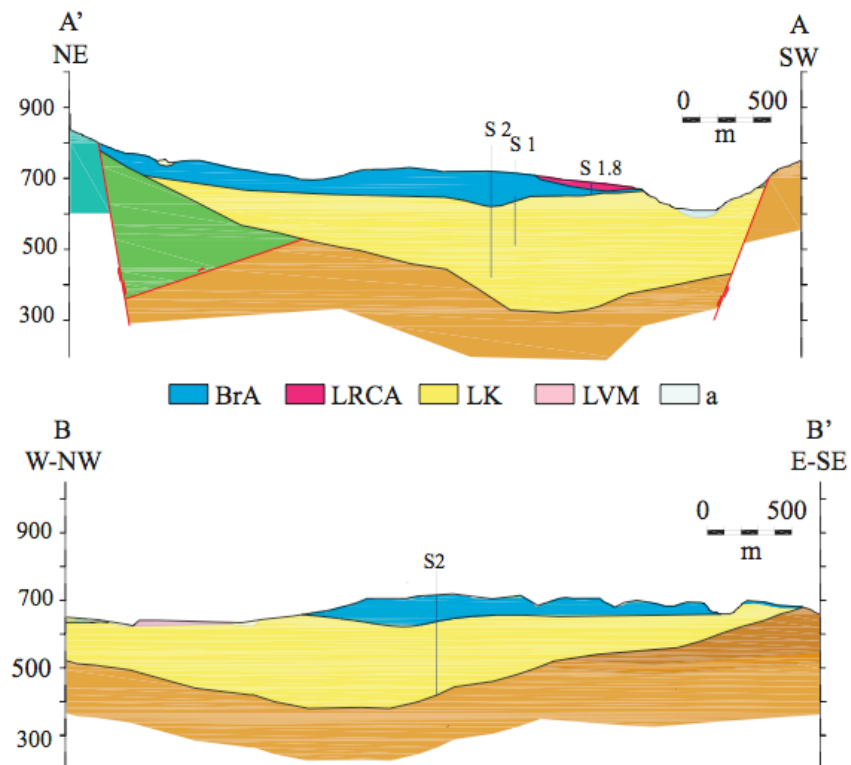


Fig. 2. Geological cross-sections

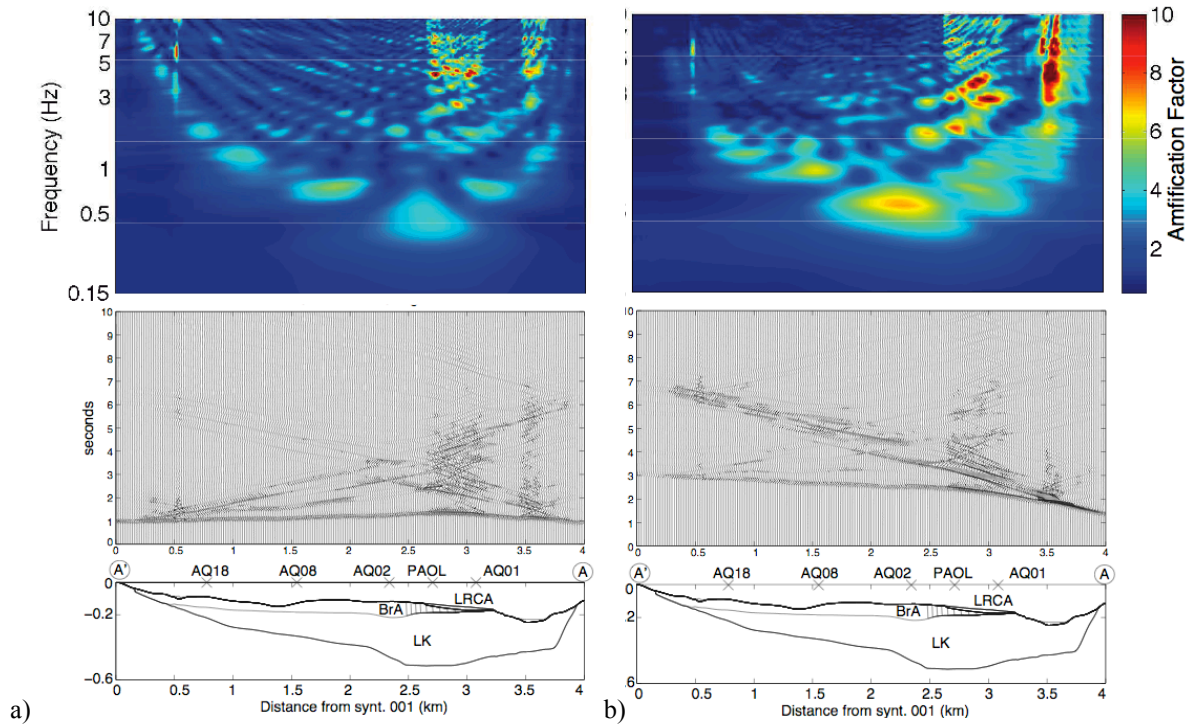


Fig. 3. AA' model: Synthetics spectral ratios (top) and displacement time series (bottom) for 0° (a) and 90° (b) incident SH wave, the latter entering the model from the right-hand side. The bedrock reference is on that side for both angles of incidence. Mechanical parameters are in Table 1

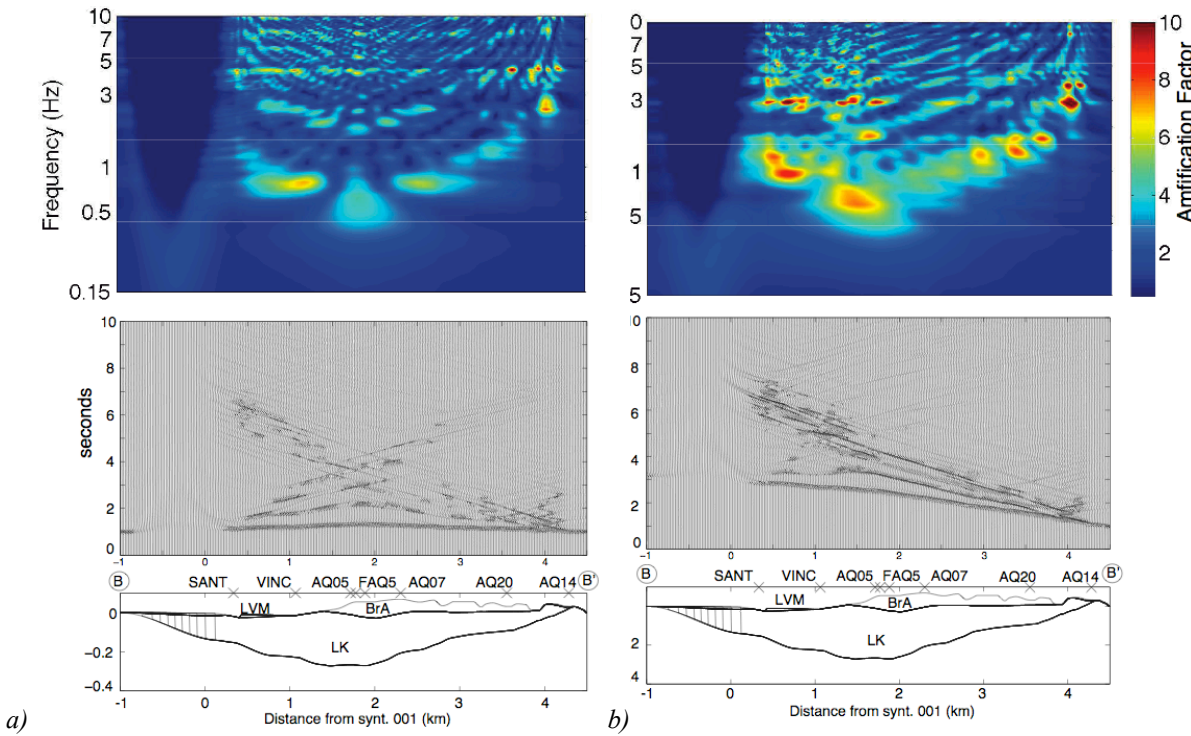


Fig. 4. BB' model: Synthetics spectral ratios (top) and displacement time series (bottom) for 0° (a) and 90° (b) incident SH wave, the latter entering the model from the right-hand side. The bedrock reference is on that side for both angles of incidence. Mechanical parameters are in Table 2

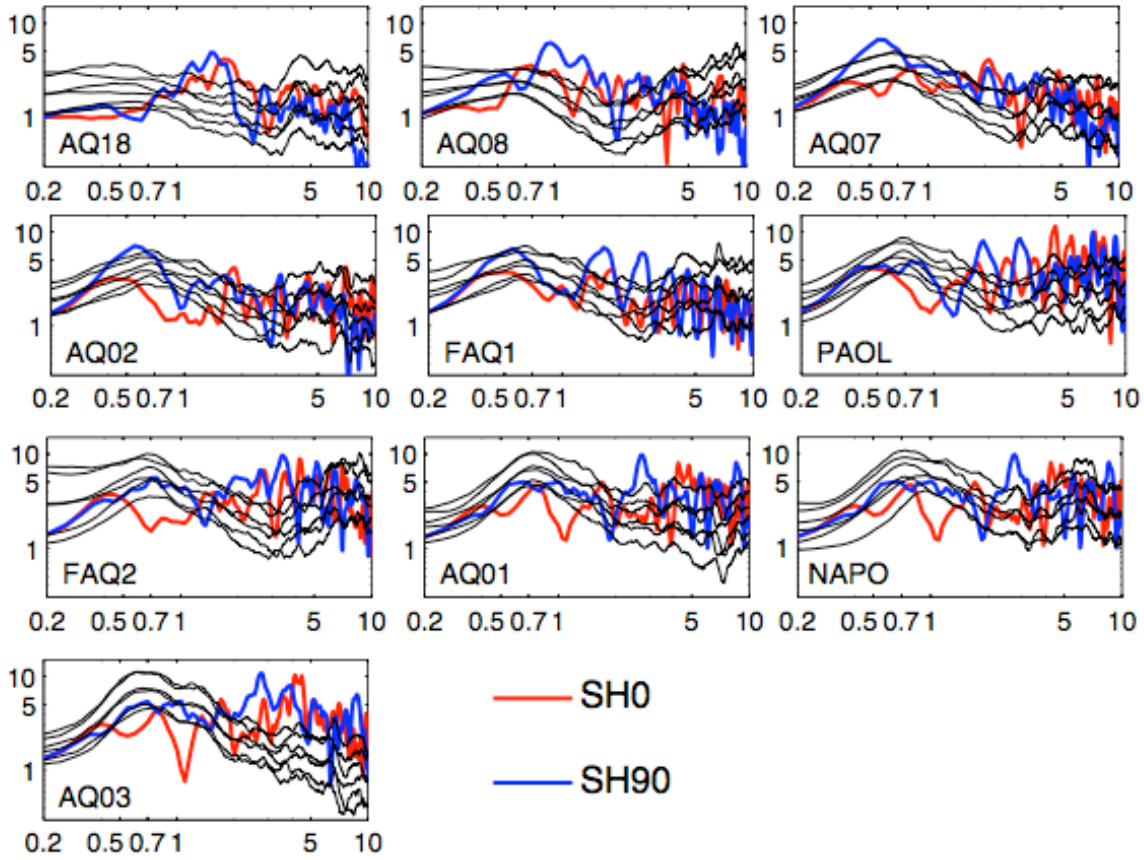


Fig. 5. AA' model: Synthetics spectral ratios in colored lines vs earthquakes horizontal with standard deviation all in black. Reference is at right-hand side of the model. Sites are listed from NE (AQ18) to SW (AQ03).

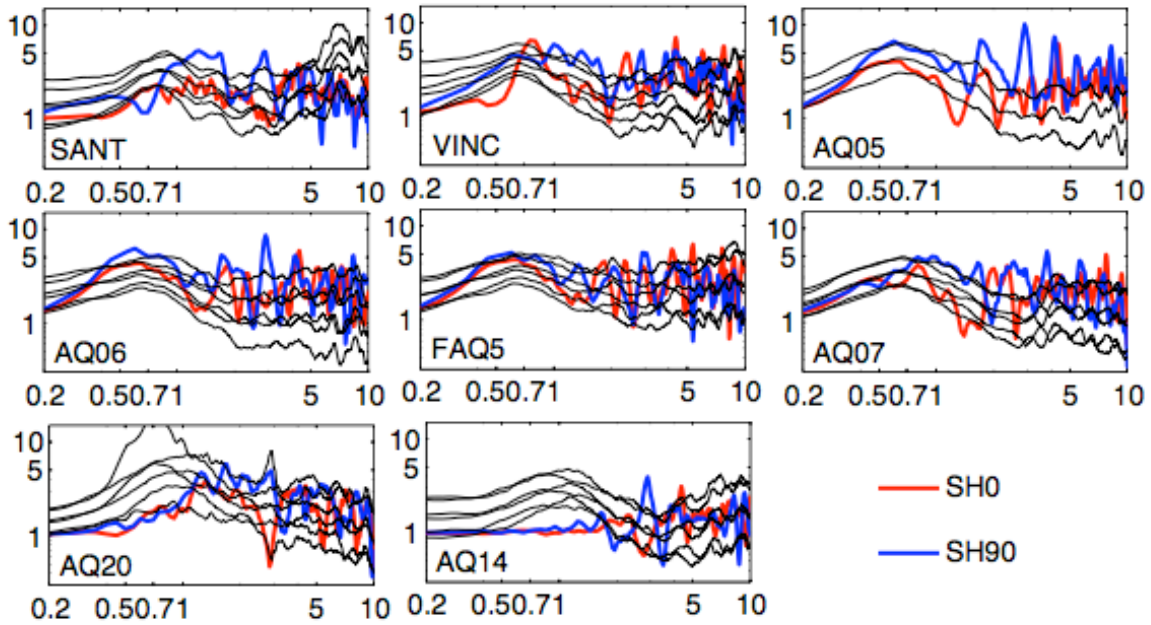


Fig. 6. BB' model: Synthetics spectral ratios in colored lines vs earthquakes horizontal with standard deviation all in black. Reference is at right-hand side of the model. Sites are listed from WNW (SANT) to ESE (AQ14).

TABLES

Table 1. Mechanical parameters for Profile AA'
(Vs has a horizontal gradient in BrA)

Layer	Distance from x=0	rho (g/cm3)	Vs (m/s)	1/Qs	Vp (m/s)	1/Qp
a	0	1700	350	0.003	1000	0.006
	5000	1700	350	0.003	1000	0.006
LRCA	0	1700	350	0.01	1000	0.05
	5000	1700	350	0.01	1000	0.05
BrA	0	2000	900	0.01	1800	0.005
	2438	2000	900	0.01	1800	0.005
	2477	2000	880	0.01	1800	0.005
	3188	2000	520	0.01	1800	0.005
	3227	2000	500	0.01	1800	0.005
	5000	2000	500	0.01	1800	0.005
LK	0	1900	725	0.015	1800	0.03
	5000	1900	725	0.015	1800	0.03
Bedrock		2300	2500	0.005	3400	0.0025

Table 2. Mechanical parameters for Profile BB'
(1/Q has a horizontal gradient on the left-hand side of the model;
Vs has a vertical gradient in LVM: Vs* at top of layer, Vs^ at bottom of layer)

Layer	Distance from x=0	rho (g/cm3)	Vs (m/s)	1/Qs	Vp (m/s)	1/Qp
BrA	-1000	2000	900	10	1800	10
	376	2000	9000	0.01	1800	0.005
	4500	2000	900	0.01	1800	0.005
LVM	-1000*	1900*	450*	0.0015*	1800*	0.003*
	-1000^	1900^	650^	0.0015^	1800^	0.003^
	4500*	1900*	450*	0.0015*	1800*	0.003*
	4500^	1900^	650^	0.0015^	1800^	0.003^
LK	-1000	1900	725	10	1800	10
	376	1900	725	0.0015	1800	0.003
	4500	1900	725	0.0015	1800	0.003
Bedrock		2300	2500	0.005	3400	0.0025

REFERENCES

Amoroso S, Del Monaco F, Di Eusebio F, Monaco P, Taddei B, Tallini M, Totani F, Totani G [2010] Campagna di indagini geologiche, geotecniche e geofisiche per lo studio della risposta sismica locale della città dell'Aquila: la stratigrafia dei sondaggi [Giugno - Agosto 2010]. Report CERFIS n. 1, http://www.cerfis.it/en/download/cat_view/67-pubblicazioni-cerfis/68-reports

Bordoni P, Di Giulio G, Haines AJ, Milana, F. Cara, G, Rovelli A [2010] Issues in choosing the references to use for spectral ratios from observations and modeling at Cavola Landslide in Northern Italy. *Bull Seism Soc Am*. doi:10.1785/0120090116

P. Bordoni, J. Haines, G. Milana, S. Marcucci, F. Cara and G. Di Giulio [2011], Seismic response of L'Aquila downtown from comparison between 2D synthetics spectral ratios of SH, P-SV and Rayleigh waves and observations of the 2009 earthquake sequence, *Bulletin of Earthquake Engineering*, 9-3, 761-781, DOI: 10.1007/s10518-011-9247-5

De Luca G, Marcucci S, Milana G, Sano' T [2005] Evidence of low frequency amplification in the city of L'Aquila, Central Italy, through a multidisciplinary approach including strong and weak-motion data, ambient noise, and numerical modeling. *Bull Seism Soc Am* 95[4]:1469-1481

Haines AJ, Hulme T, Yu J [2004] General elastic wave scattering problems using an impedance operator approach—I. Mathematical development. *Geophys J Int* 159:643-657

Hulme T, Haines AJ, Yu J [2004] General elastic wave scattering problems using an impedance operator approach—II. Two-dimensional isotropic validation and examples. *Geophys J Int* 159:658-666

Kennett BLN [1983] *Seismic wave propagation in stratified media*. Cambridge University Press, Cambridge

Milana G, Azzara RM, Bergamaschi F, Bertrand E, Bordoni P, Cara F, Cogliano R, Cultrera G, Di Giulio G, Duval AM, Fodarella A, Marcucci S, Pucillo S, Régnier J, Riccio G [2011] The contribution of seismic data in microzonation studies for downtown L'Aquila. *Bull Earthquake Eng*.doi:10.1007/s10518-011-9246-6

Gruppo di lavoro MS_AQ [2010] *La Microzonazione Sismica dell'area aquilana*. 2 vol + 1 DVD