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1-D Theoretical Modeling for Site Effect Estimations in Thessaloniki: Comparison with Observations

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Abstract—We apply an algorithm based on the modal summation method to theoretically estimate the site effect at selected locations underlain by different geological formations within the city of Thessaloniki (Greece). Complete strong motion synthetics are constructed for all components of motion at each site, for a maximum frequency of 10 Hz. The anelastic, local 1-D velocity models are based on cross-hole data. Four point sources with different azimuths and distances from the city are used to compute the input signals. The theoretical amplification is estimated through spectral ratios of accelerograms obtained by the local 1-D over those obtained by the regional 1-D velocity model. The results from the numerical modeling are compared with those derived from experimental techniques, such as of Standard Spectral Ratio and Horizontal-to-Vertical Spectral Ratio, which had been applied to acceleration data recorded at the same sites. The comparison demonstrates that the theoretical amplifications based on known and simple subsurface geology can be used as a first-order estimate, while for cases of more complex geometries the use of at least 2-D modeling in site effects estimation is mandatory.

Key words: Modal summation modeling, spectral ratios, Thessaloniki (Greece).

Introduction

Several numerical techniques have thus, far been developed for the estimation of ground-motion amplification since the pioneer work by THOMSON (1950) and HASKELL (1953), and applied in microzonation studies. Their significance is considerable, in that they can provide synthetic signals especially for areas with no recordings available. Even when observations are available, they are useful for the validation of the method. Moreover, especially in highly populated urban areas, their contribution for the design of earthquake-resistant structures is very important since they make estimates possible without need to expect an earthquake to occur. Although many methods have been used to study the effects of lateral heterogeneities, methods for 1-D earth models will, however, continue to maintain their importance and find applications in several studies, mainly because of their low cost

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and short computation time. In this study we complement the work of TRIANTAFYLLIDIS *et al.* (1999), who applied the modal summation method to produce synthetic accelerograms only for P-SV waves and compared the estimated amplification of the radial component with the one obtained by applying SSR to a set of observed accelerograms.

Method Used

For the construction of our synthetic accelerograms we applied an algorithm based on the modal summation method (PANZA, 1985; PANZA and SUHADOLC, 1987; FLORSCH *et al.*, 1991). The modal summation method is a powerful tool that can be used to compute broadband seismograms by simulating the wave propagation from the source position to the lateral heterogeneity of interest. The path from the source to the site of interest can be approximated by a structure composed of flat, homogeneous anelastic layers.

The seismograms computed contain all body waves and surface waves, while the use of the modal summation method also permits the treatment of extended sources, which can be modeled by a sum of point sources appropriately distributed in time and space, allowing the simulation of a realistic rupture process on the fault. The modal summation method is practically free from approximations in the relatively simple one-dimensional case and can be efficiently extended, introducing approximations of variable and to some extent quantifiable size, to two- and three-dimensional cases (VACCARI *et al.*, 1989), while it can also be applied for a quantitative and realistic earthquake hazard assessment (PANZA *et al.*, 1996).

Data

We used the known geometry and the dynamic soil properties (densities, body-wave velocities and quality factors) at 11 selected sites (Fig. 1) within the city of Thessaloniki (PITILAKIS *et al.*, 1992; RAPTAKIS *et al.*, 1994). The detailed geotechnical information for the first superficial meters (up to the depth of bedrock) was derived from a series of geotechnical tests and extended geophysical surveys (cross-hole and down-hole measurements, seismic surveys, surface-wave inversion) that have been carried out by the Laboratory of Soil Mechanics and Foundation Engineering of Aristotle University of Thessaloniki throughout the city. Below the boreholes' maximum depth, the values of *P*- and *S*-wave velocities (V_P and V_S) and quality factors (Q_P and Q_S) were gradually increased up to the depth of 1 km composing the local velocity model. Figure 2 shows the *P*- (V_P) and *S*-wave (V_S) velocity models that were used at each site for the first kilometer of depth. Under the local velocity model (i.e., below 1 km of depth) each site is

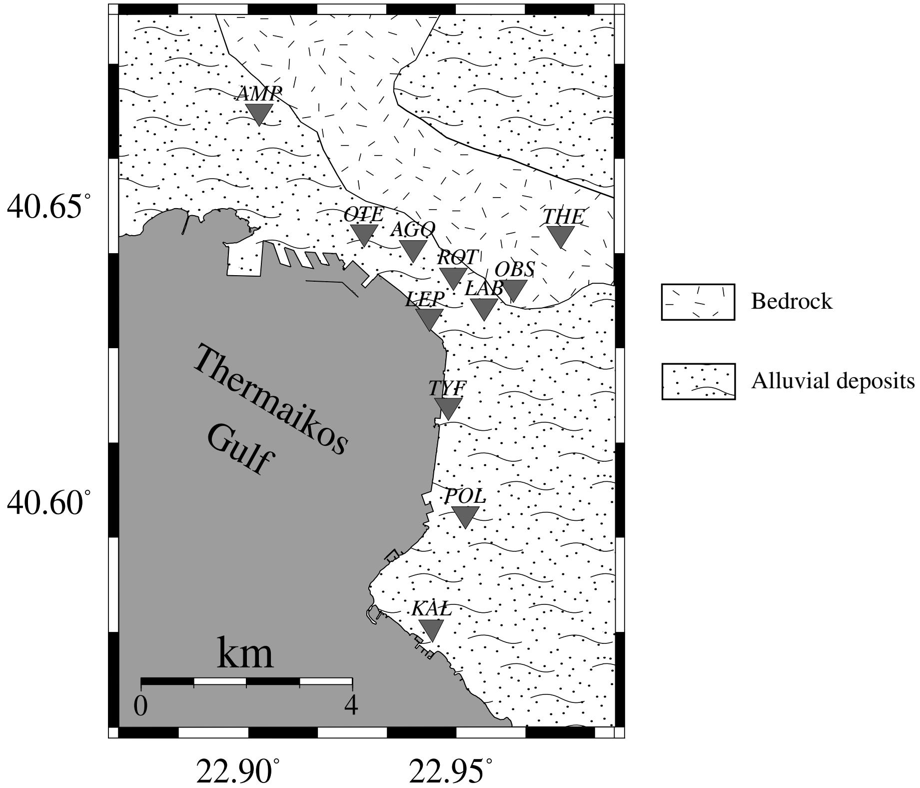

Figure 1
Map of the city of Thessaloniki showing the sites under examination (modified after RAPTAKIS, 1995).

underlain by the regional velocity model which has been deduced from the work in the area of Volvi basin done by PAPAZACHOS (1998) and LIGDAS and LEES (1993). According to the regional velocity model, V_P and V_S start increasing from 4850 m $\cdot$ sec^{-1} and 2800 m $\cdot$ sec^{-1}, respectively, while Q_P and Q_S are 250 and 200, respectively. The local velocity model of sites OBS and THE, located on bedrock, coincides with the regional velocity model, whose velocity at 1 km is extended to the surface.

The modal summation method was employed for the construction of synthetic accelerograms at each site for all components of motion and for frequencies up to 10 Hz. The synthetic accelerograms were generated by the four double-couple point sources shown in Figure 3, which are located at different distances and azimuths from the examined sites, although in the same areas where seismicity is observed (Table 1). The location of one of these events (#1, Table 1) corresponds to that of the destructive earthquake of June 20 ($M_S = 6.5$) which hit Thessaloniki in 1978 (SOUFLERIS and STEWART, 1981). A second event (#4, Table 1) is located in the area

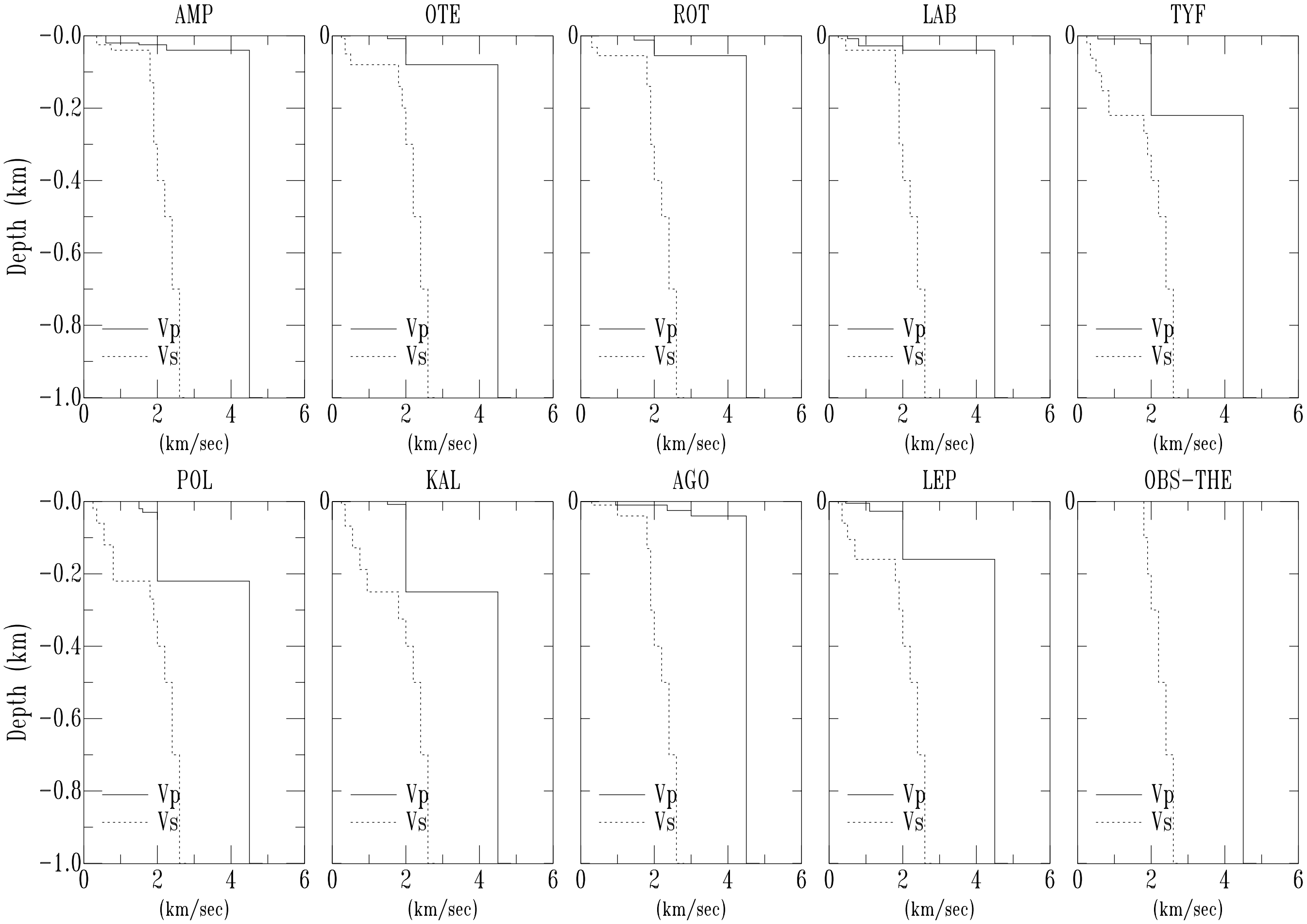

Figure 2
The local 1-D velocity models used at each site up to the depth of 1 km.

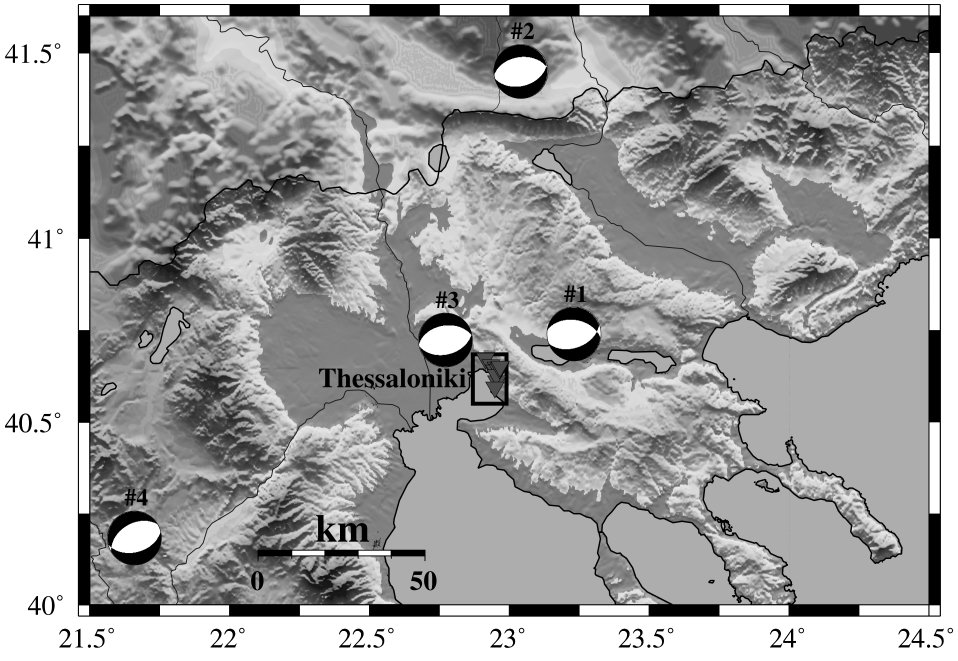

Figure 3
The four point sources used for the 1-D simulations. The number above the focal mechanism denotes the corresponding event number from Table 1. The black box determines the boundaries of the area shown in Figure 1.

Table 1

Catalogue of the earthquakes used for the construction of the synthetics. Z stands for source depth while R indicates the mean epicentral distance from the city

I/N	Date	Lat. N°	Lon. E°	M_S	Z (km)	R (km)	Strike	Dip	Rake
1	780620	40.740	23.230	6.5	8	27	278°	46°	−70°
2	931222	41.450	23.040	3.3	5	92	76°	45°	−94°
3	940123	40.724	22.772	2.3	5	18	76°	45°	−94°
4	950513	40.183	21.660	6.6	14.2	120	240°	45°	−101°

of the Kozani earthquake of May 13, 1995 ($M_S = 6.6$) (HATZFELD *et al.*, 1997). The remaining two locations are related to areas of low seismicity, and the used fault plane solutions (#2 and #3, Table 1) are representative of the active stress field at the area of northern Greece (PAPAZACHOS and KIRATZI, 1996). In Figure 4 we display all the components of the synthetics for the local and the regional model simulating earthquake #3 of Table 1.

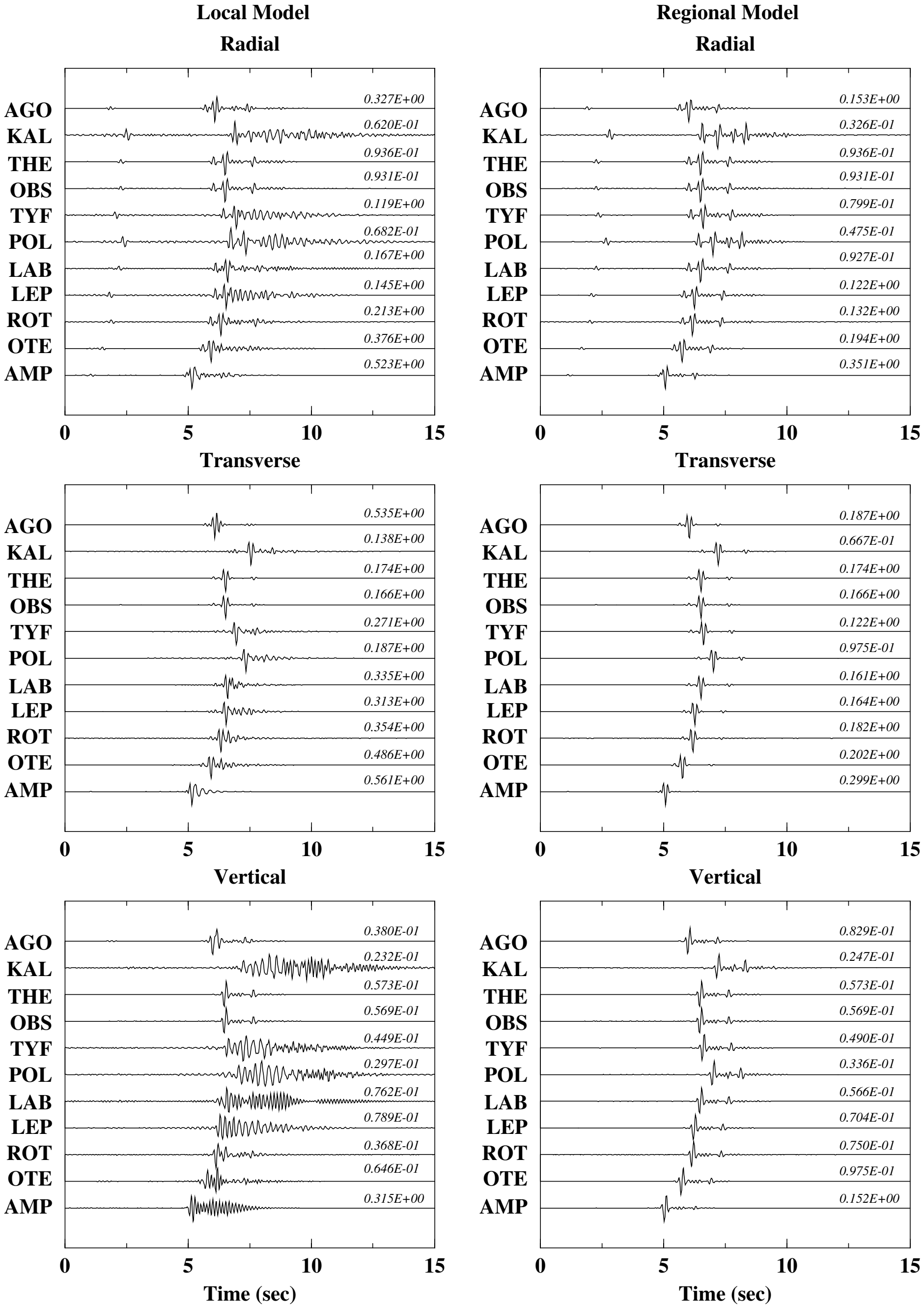

Figure 4

Radial (top), transverse (middle) and vertical (bottom) components of synthetics obtained for the local (left) and the regional (right) 1-D velocity model at each station due to a point source located west of the city (#3 on Table 1). In order to enhance the low frequency part of the signal, we smoothly filtered the waveforms with a Gaussian filter from 4 Hz to 10 Hz.

Spectral Ratios

For all the above events we have calculated the ratios of spectra of accelerograms obtained by the local 1-D over those obtained by the regional 1-D velocity model. We have also computed the spectral ratios between the local 1-D accelerograms and those of the site OBS, which was located on bedrock. TRIANTAFYLLIDIS *et al.* (1999) used site OBS as a reference site when they applied the experimental technique of Standard Spectral Ratio (SSR) to their observed set of accelerograms. All spectra have been smoothed with a running average frequency window of 0.5 Hz with a 50% overlap.

It is evident that the local-to-regional spectral ratio differs from local-to-OBS, since the former is a division between spectra computed at the same station, while the latter is between spectra of accelerograms at two different stations. This difference produces an underestimation of the amplitude level of the closer events, since for these events the differences in distance and azimuths between the accelerograms are more considerable. Therefore, we have corrected the local-to-OBS ratios of the two closer events by multiplying them by the ratio of peak ground acceleration (PGA) calculated at OBS over the site's PGA for the regional model. In this way the source and radiation pattern effects for the local-to-OBS spectral ratios were minimized and the amplification obtained is due mainly to the local velocity model. We noticed that for the two distant events, whose source-receiver distance is considerably further than the interstation distances, the energy of motion dominates at frequencies below 3 Hz. Also, the estimated amplification in this frequency range, which depends on the geometry of the "deeper" part of the model, is better determined. Conversely, for the events with short source-receiver distances, the energy is essentially at frequencies higher than 3 Hz and the amplification estimates depend more on the geometry and the characteristics of the superficial layers. Figure 5 shows the variation of the local-to-regional spectral ratios of all the events at two sites: TYF and AGO, where there is observation of the maximum and minimum standard deviations of the four ratios, respectively. After the "correction" we applied to the closer events, the local-to-OBS ratios were almost consistent in terms of spectral shape and amplification level as well as in the frequencies where the amplification peaks appear with the local-to-regional ratios. Therefore, in Figure 6, we show only the means of the four local-to-regional spectral ratios for each component of motion at all sites. The two horizontal ratios are nearly consistent, while the vertical one presents deep troughs at frequencies that differ from site to site. After examining the variation of ellipticity with frequency for the first 10 modes at all examined sites, we concluded that this might be the main reason for the strong de-amplification of the vertical component in Figure 6. At some frequencies the ellipticity (i.e., the ratio between the radial and the vertical components of motion) approaches infinity, namely all the energy of motion is turned into the radial or the vertical component for those particular frequencies. By taking the ratios of spectra we gain strong amplifications in radial component and strong de-amplifications in the vertical component. At TYF, KAL, LEP and POL

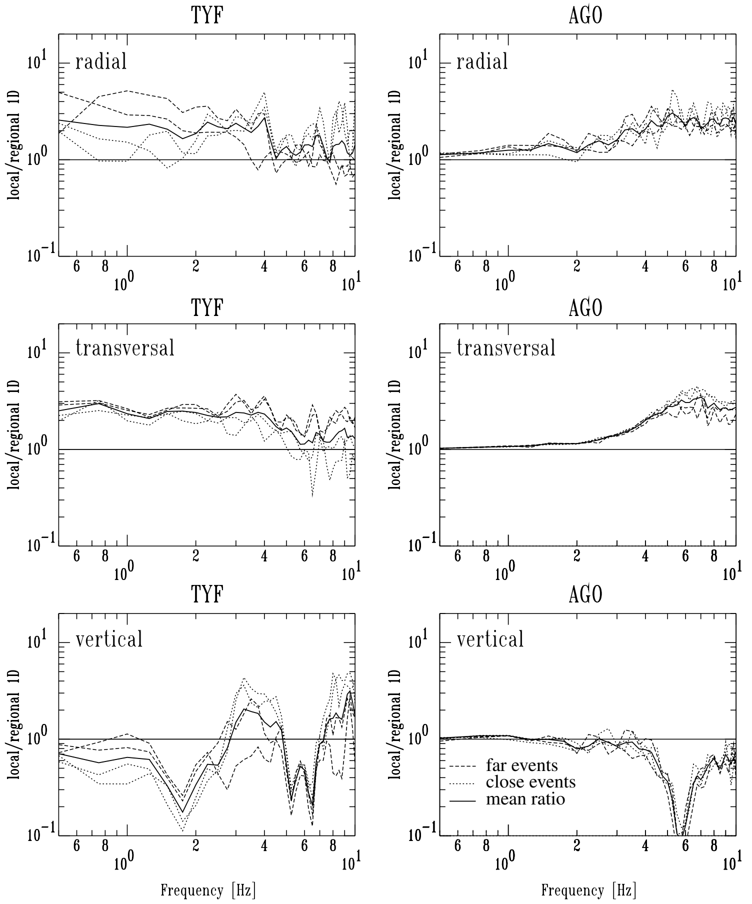

Figure 5
Local-to-regional 1-D spectral ratios of the four events at sites TYF (left) and AGO (right). Solid line represents the mean of all four ratios.

where the sedimentary cover is thick, this effect is observed at low frequencies, while at AGO, LAB, AMP (presence of thinner cover) the effect is noticed at higher frequencies.

Next we calculated the spectral ratios of horizontal to vertical components of the accelerograms of the local velocity model. A horizontal component is simply defined as the average of the radial and the transversal components of all four events.

Comparison with Observations

Figure 7 illustrates the comparison of the mean of spectral ratios of theoretical local-to-OBS 1-D model for the horizontal components with the mean of the SSR

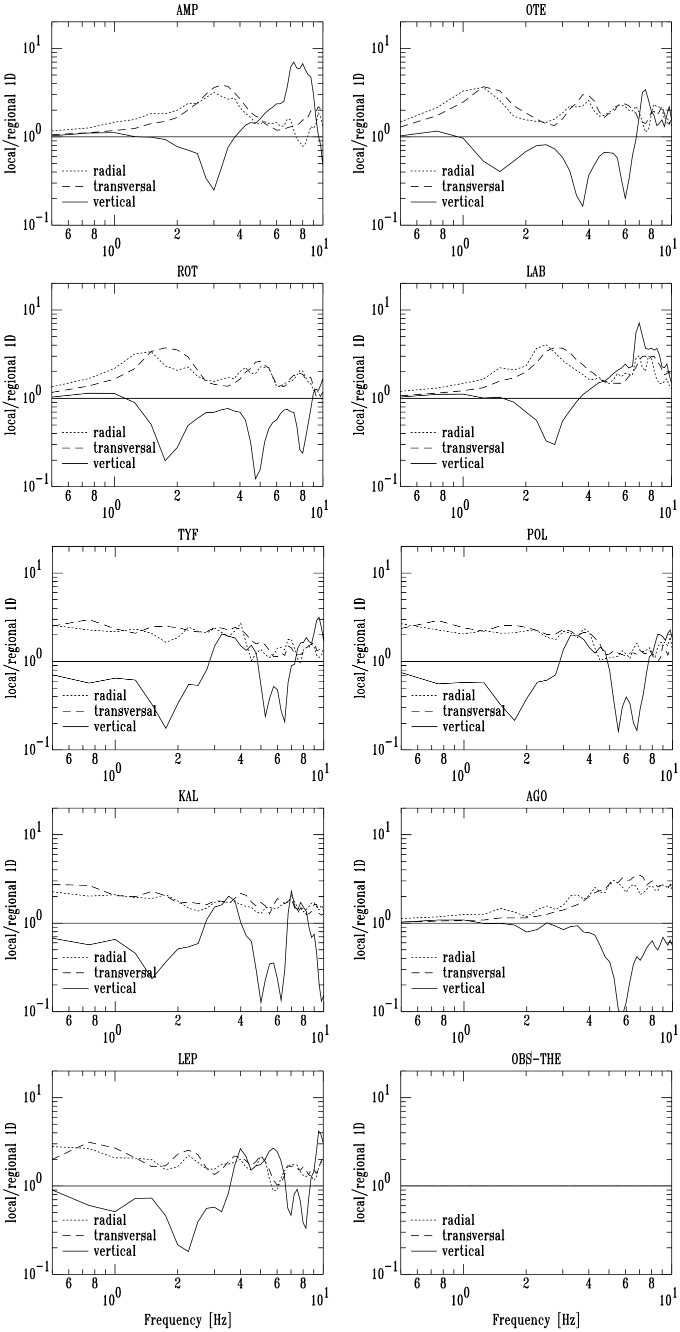

Figure 6

Local-to-regional 1-D mean spectral ratios at each site for all components of motion of the four events.

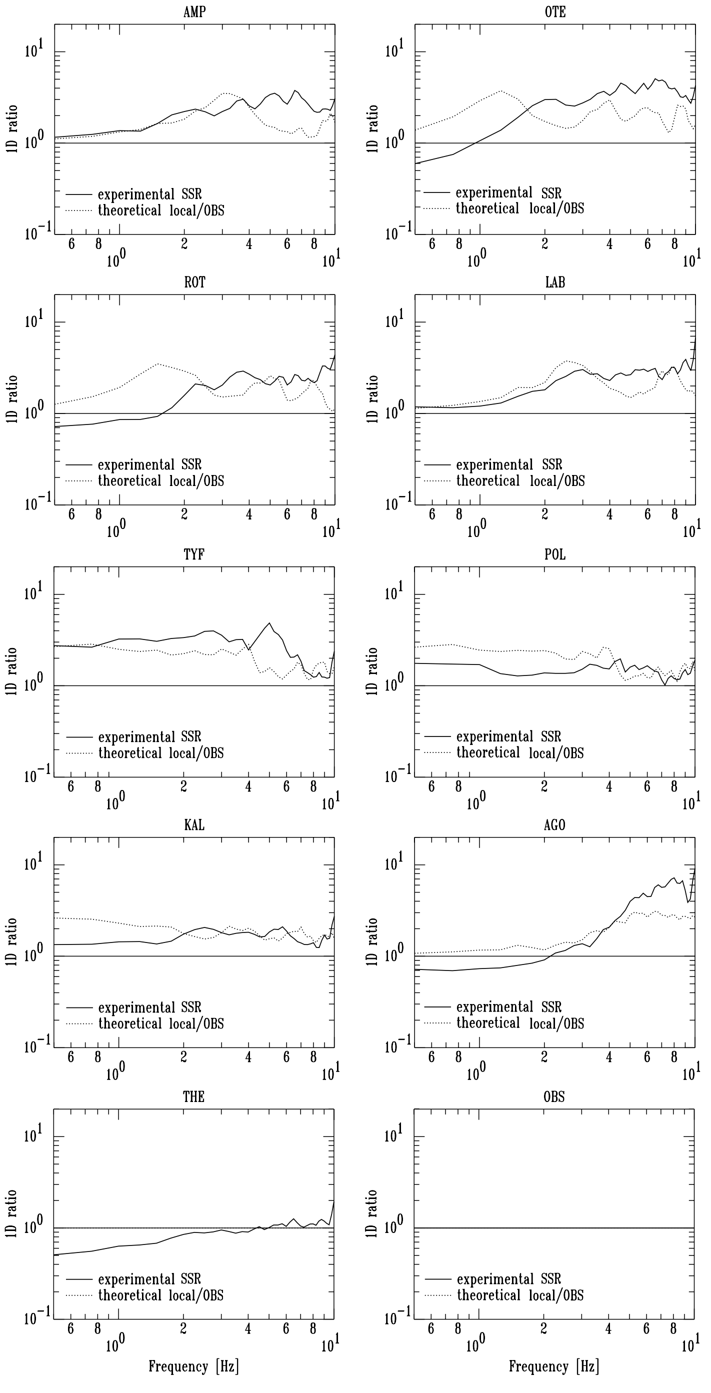

Figure 7
Comparison between the mean of spectral ratios of theoretical local-to-OBS 1-D model for the horizontal component (dotted line) with the mean of the SSR method derived from the experimental data (solid line).

(Borcherdt, 1970) derived from the experimental results of Triantafyllidis *et al.* (1999). It must be annotated that the same smoothing had been applied to the set of the experimental spectra. At site LEP there were no recorded data and therefore no comparison is made. In general at all sites both ratios are comparable, which means that our theoretical 1-D estimates represent a rather good preliminary estimation of the expected amplification level. There are sites where the agreement is good in the complete frequency range (LAB, POL, KAL), while at others it is good only for the lower frequencies (AMP, TYF, AGO) or for the higher ones (ROT). At OTE the two ratios differ in the whole frequency range. The main tendency is that the amplification level of the theoretical ratio is higher at frequencies below 4 Hz (with the exception of TYF), while for higher frequencies the opposite is observed. Some discrepancies can be due on one hand to the fact that the experimental ratio is the average of 34 recorded events, while the theoretical is the average of only four events. On the other hand, the 2-D and 3-D effects in the wave propagation, which have not been taken into account in our 1-D modeling, seem to affect significantly the incoming wavefield at some sites (e.g., OTE).

Theoretically it appears that the vertical component of ground motion is not affected by local site conditions as much as the horizontal components and may be thus used to measure the "incident" ground motion (e.g., Singh *et al.*, 1988; Campillo *et al.*, 1989; Chávez-Garcia, 1991). However, Riepl *et al.* (1998), Raptakis *et al.* (1998) and Triantafyllidis *et al.* (1999) demonstrated that the vertical component can be strongly affected by local amplification effects if the geology is rather complex. The last result is also supported by Figure 8 where the mean of vertical local-to-OBS ratios at each site is compared with the mean amplification obtained with the SSR method applied to vertical components (VSSR) by Triantafyllidis *et al.* (1999). Except for the case of AGO, where there is an agreement between the two ratios up to 4 Hz, at all the other sites a significant disagreement is observed. As expected, in most cases the experimental ratio exceeds the theoretical one in the entire frequency band.

Since for most real cases 1-D model is hardly a good model for wave propagation, the strong de-amplification of the vertical component (Fig. 6) is a theoretical result, as long as surface waves play some role. For small events at close distances there are few surface waves developed, thus this effect is not well seen on experimental records. Due to those discrepancies between the estimated and the observed amplification of the vertical component, the ratios of the horizontal to vertical components for the local model present significant inconsistencies when compared with the mean amplification obtained by the HVSR experimental technique (Triantafyllidis *et al.*, 1999). Only in a couple of cases (THE, AGO) there is a similarity in spectral shape, while at all sites the theoretical ratio overestimates the experimental one (Fig. 9). In fact, we usually see only the fundamental frequency, and that is also detectable by Nakamura's technique: the maximum coincides with the ellipticity "infinite" for the layer over half-space model (Panza, 1985; Bard, 1998).

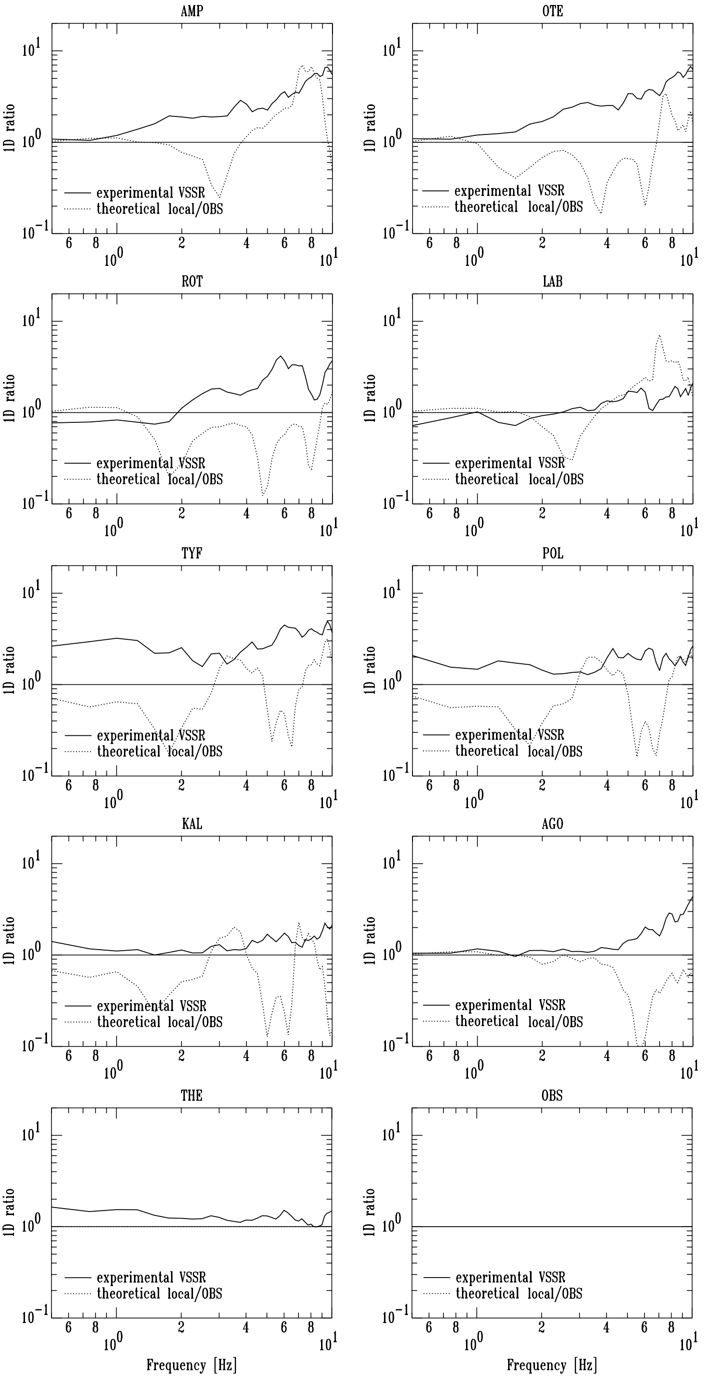

Figure 8
Comparison between the mean of spectral ratios of theoretical local-to-OBS 1-D model for the vertical component (dotted line) with the mean of the SSR method applied to vertical component (VSSR) and derived from the experimental data (solid line).

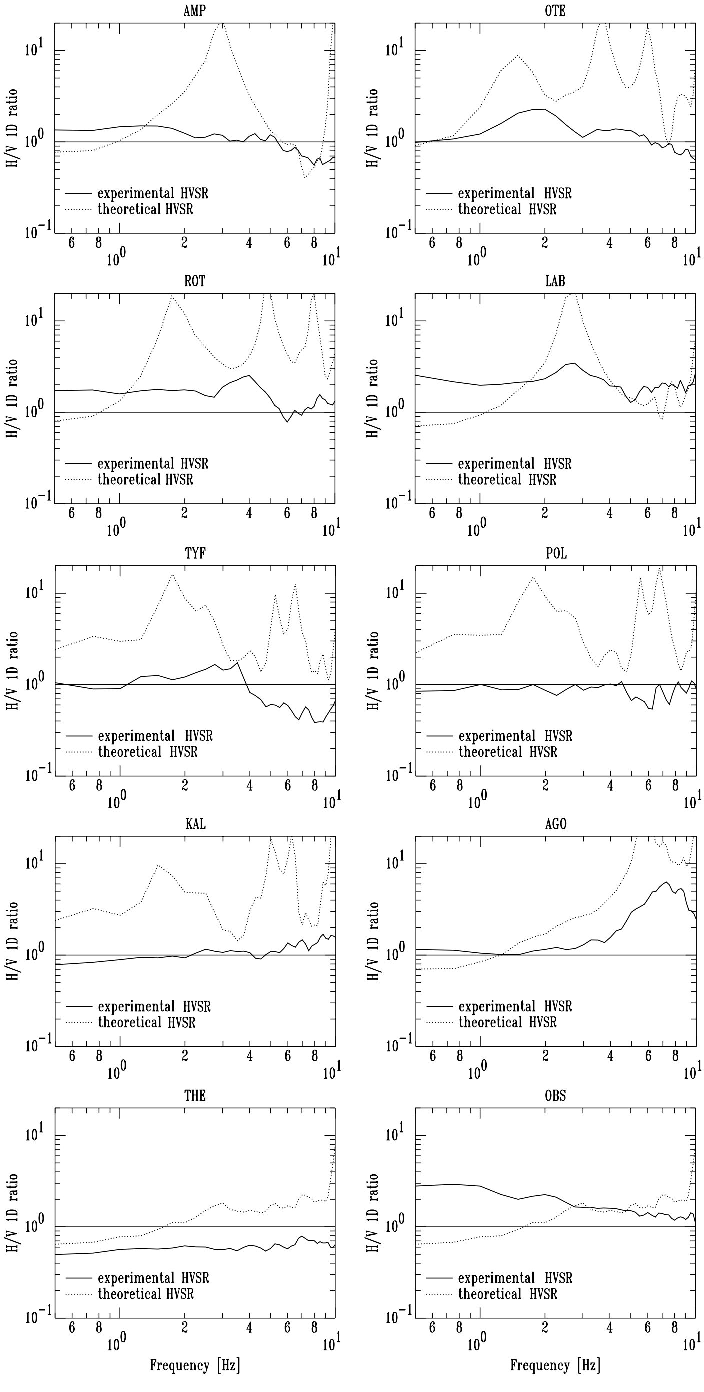

Figure 9
Comparison between the mean of spectral ratios of theoretical horizontal-to-vertical (dotted line) with the mean of the HVSR method derived from the experimental data (solid line).

Conclusions

The comparison between the amplifications obtained by the application of the 1-D modal summation method and the experimental method of Standard Spectral Ratio (SSR) indicates that the theoretical amplifications based on known subsurface geology can be used as a first-order estimate. At most sites with simple planar geometries, theoretical 1-D estimates fit rather well with the amplification derived from observed records. Conversely the results obtained by the comparison between the theoretical and experimental horizontal-to-vertical spectral ratios are less encouraging. The difference between the estimated and observed amplification of the vertical component leads to upshots that cannot be applied for the preliminary estimate of the site transfer function, since the amplification of the vertical component is a reality in some circumstances as those presented. Therefore, the HVSR method can lead to erroneous results, and the SSR for vertical component (VSSR) is not reliable either due to wrong assumptions. Moreover, in cases of more complex geology, where the lateral heterogeneities are not negligible, 2-D and possibly 3-D effects should be considered with an appropriate modeling.

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