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PART II: Comparison of Theoretical and Experimental Estimations of Site Effects

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Abstract — To check the reliability and the quality of the theoretically estimated ground responses obtained from the 2-D simulation by the application of the hybrid method in PART-I, we compare some of them with those obtained at the same sites from observed data using the Standard Spectral Ratio (SSR). The comparison validates our synthetic modeling and shows that in cases of complex geometries, the use of at least 2-D numerical simulations is required in order to reliably evaluate site effects and thus facilitate the microzonation of the city of Thessaloniki.

Key words: Experimental records, Standard Spectral Ratio, numerical modeling.

Introduction

The unequal distribution of damage from earthquakes that occurred during the last two decades both worldwide (e.g., MEXICO 1985, LOMA PRIETA 1989, NORTHRIDGE 1994, KOBE 1995, ISMIT 1999) and in Greece (e.g., THESSALONIKI 1978, KALAMATA 1986, KOZANI 1995, ATHENS 1999) is still a challenge to seismologists and earthquake engineers. In the last decade the causes for this differentiation in seismic motion have been looked for in the characteristics of the source, the properties of the propagation path as well as the geological features of the recording site (e.g., AKI, 1988, 1993; KUDO, 1995; BARD, 1997). Many researchers have worked on the estimation of local site effects with experimental methods, as well as on the improvements of existing or development of new experimental techniques (e.g., BORCHERDT, 1970; NOGOSHI and IGARASHI, 1971; LANGSTON, 1979; NAKAMURA, 1989).

Even if this intense research has led to an understanding of the broad reasons of the spatial variation of ground response, many details of it remain unexplained. This is due to the fact that there is a variety of parameters that can affect the final

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result, making the modeling of site effects rather challenging. The parameters of the seismic source (e.g., seismic moment, stress drop, mechanism, fracture characteristics and the spectral content of the released energy) can have a non-negligible influence on site effects (e.g., TRIANTAFYLLIDIS *et al.*, 2002). In fact, they control the generation of the wavefield which is propagated in the numerical simulations (e.g., CRANSWICK, 1985). The effect of the propagation path is related to the amplitude of seismic waves, to the type of waves and angle of incidence of the seismic wavefield on the analyzed site. Only at the end we have to account for the influence of the geometrical and dynamical parameters of the layers under the investigated site.

Thus, to understand and explain the observations we need theoretical modeling of the wavefield generation and propagation. Theoretical methods are especially useful in seismic design, since the recordings from major earthquakes at areas with dense networks of instruments are relatively rare. We also need efficient methods to estimate the ground response before the occurrence of the next earthquake and the sole means of achieving this is again through detailed numerical modeling.

Such theoretical estimates need, however, always to be thoroughly checked against observations, wherever possible. This is a rather difficult task, since methods to estimate ground response from observations are not unique and can be subject to strong criticism (e.g., the so-called Nakamura's method). It is also sometimes impossible (e.g., when the source is not known) to numerically model the experimentally derived estimates.

In this paper we compare the theoretical ground response estimates obtained from the application of the hybrid method (TRIANTAFYLLIDIS *et al.*, 2004) with the ones obtained from the experimental method of SSR (TRIANTAFYLLIDIS *et al.*, 1999).

Experimental and Theoretical Spectral Ratios

The experimental ratios used in the comparison were acquired by applying the Standard Spectral Ratio (SSR) method to a set of accelerograms recorded by RefTek stations equipped with CMG-5 accelerometers during a four-months period (November 1993-February 1994) at different sites within Thessaloniki (TRIANTAFYLLIDIS *et al.*, 1999). In this technique, also known as reference station technique, first introduced by BORCHERDT (1970) and still widely used, the records at each site are compared to the records for the same events at a nearby bedrock site (reference site) through spectral ratios. In the application of this method we will use the station OBS as a reference station, because it is located on bedrock (Fig. 1).

As discussed in TRIANTAFYLLIDIS *et al.*, (2004, this volume) we used all available geotechnical and geological information to construct seven 2-D profiles with different orientations within the city. In Figure 1, the geometry of each section is throughly

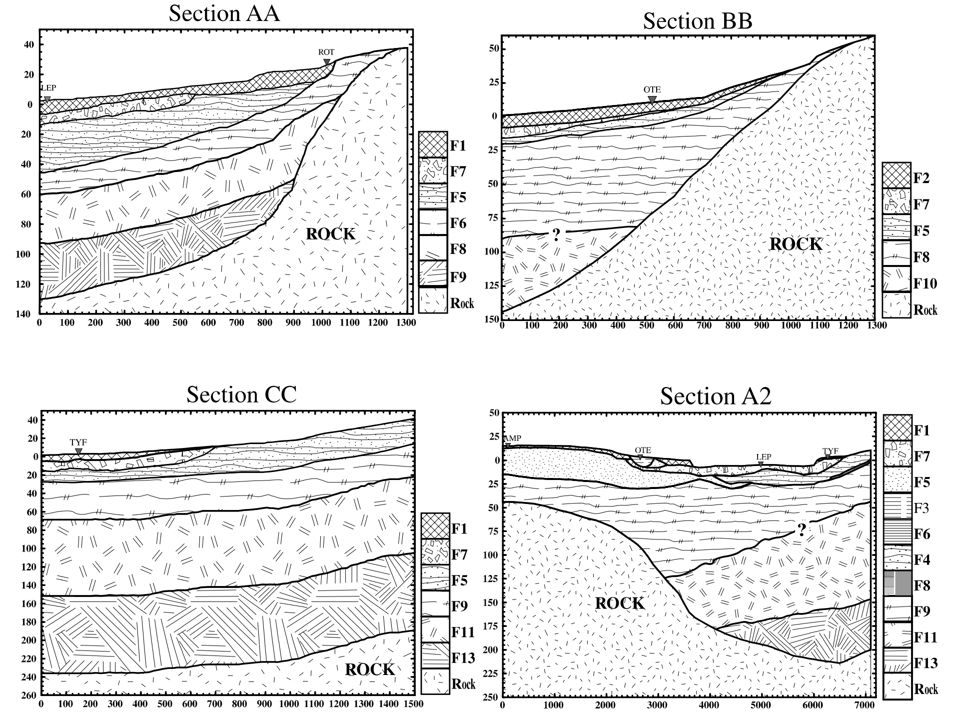


Figure 1a
Geometry of profiles AA, BB, CC and A2.

presented, as well as their position at the wide area in comparison with the other sections. The dynamic parameters that characterize the formations of each section (density, velocities and quality factors) are shown in Table 1. The question marks in sections BB, A2, A3 and A4 denote uncertainties in the formation boundaries.

The comparison between the experimental and 2-D theoretical spectral ratios has been performed for all of the events of Table 1 of PART-I at those sites of the city where the RefTek stations had been installed. Moreover, for each of the previous events the above results were also compared with the ones obtained from 1-D simulations by applying the modal summation method (PANZA, 1985; PANZA and SUHADOLC, 1987; FLORSCH *et al.*, 1991). We must note that the comparison with the results from the 1-D simulation differs from the one in the work of TRIANTAFYLLIDIS *et al.*, (1999). In that paper there is a comparison between the mean theoretical amplification of four events and the mean experimental amplification which resulted from 34 recorded events. In this paper, wherever a comparison between the seismic responses that resulted from the SSR method and the 1-D simulations takes place, we have calculated the spectral ratios between the synthetic accelerograms resulting from the local 2-D velocity model over the ones calculated at station OBS (local/

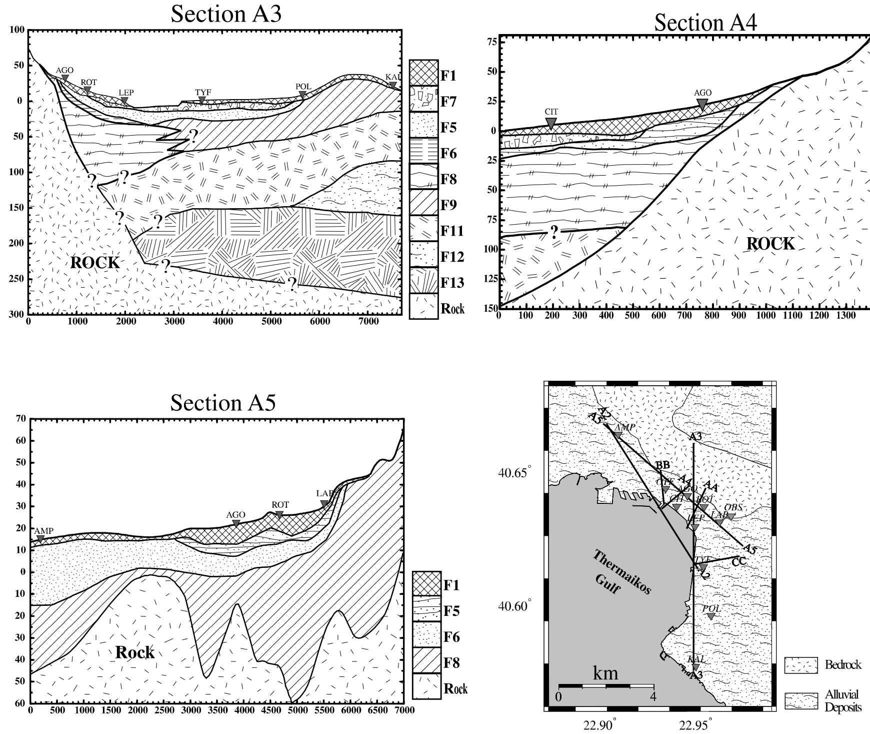


Figure 1b

The same as Figure 1a but for profiles A3, A4, A5 and their position in the wider area.

Table 1

Averaged values of densities, body wave velocities (V_P, V_S) and quality factors (Q_P, Q_S) used in the 2-D computations. The geometry of each formation is outlined in Figure 1.

Formation	Density ($g \cdot cm^{-3}$)	V_P ($m \cdot sec^{-1}$)	V_S ($m \cdot sec^{-1}$)	Q_P	Q_S
F1	1.85	450	225	60	20
F2	1.9	1750	225	60	20
F3	2.0	1600	280	100	20
F4	1.9	1700	280	50	15
F5	2.0	1700	350	60	20
F6	1.9	1800	370	50	15
F7	1.7	1600	180	70	25
F8	2.0	1900	450	50	15
F9	2.0	1600	500	70	25
F10	2.0	2000	700	60	20
F11	2.1	2500	650	100	50
F12	2.2	2800	750	120	60
F13	2.2	3200	850	150	80

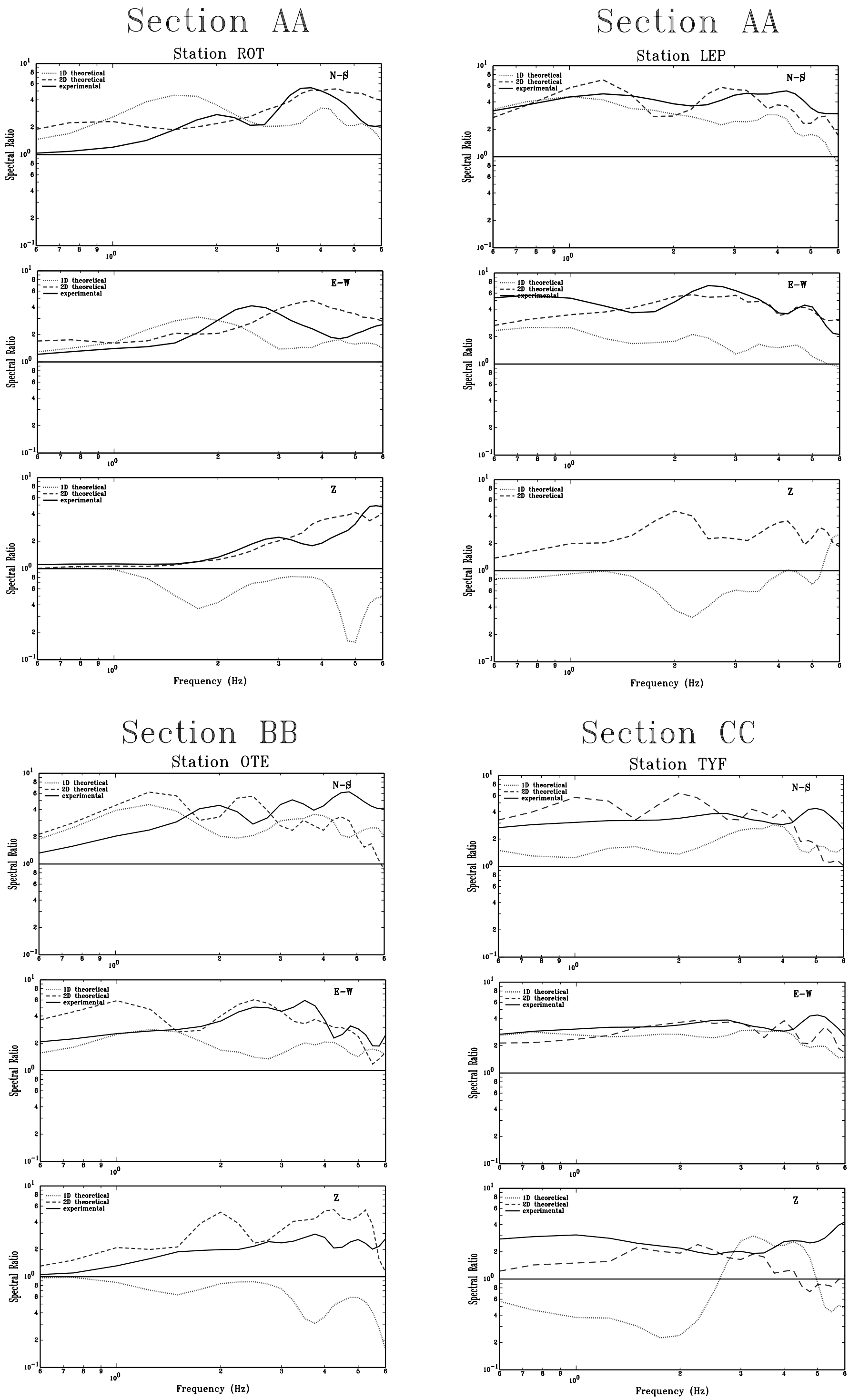
OBS). Station OBS is located on bedrock (gneiss) and its local 1-D velocity model coincides with the regional velocity model.

Comparison between Experimental and Theoretical Results

The comparison of the results (obtained by modal summation, hybrid and SSR) is performed through spectral ratios computed at the sites with earthquake recordings from RefTek stations during the field experiment (TRIANTAFYLLIDIS *et al.*, 1999). We will call such sites "instrumented sites." The spectra of the synthetic accelerograms obtained at the instrumented sites from 1-D and 2-D local velocity models are divided by the spectrum of the accelerograms computed with the modal summation method for the same source and the 1-D local velocity model at site OBS. We shall denote such spectral ratios as "local/OBS." This is done to make the comparisons possible. In fact, the application of the SSR method requires that the spectra of the horizontal components at each instrumented site are divided by the respective spectra of the same earthquake at site OBS. Along section A5 no comparison between theoretical and experimental amplifications is possible, because of the lack of records at the stations along this profile for earthquake #6 of Table 1 (PART-I). Before dividing their spectra, the horizontal synthetic waveforms were rotated in order to obtain the same orientation as that of the experimental ones (i.e., North-South and East-West). In this way the local/OBS spectral ratios are compatible with the SSR ratios and therefore the comparison with the experimental data is possible.

In Figures 2 (a, b, c and d) the comparison of the amplification obtained from SSR (continuous line) with the theoretical amplifications from the 2-D (dashed line) and 1-D simulation (dotted line) is shown for each component. At site ROT on section AA (Fig. 2a), there is a good agreement between the experimental and the 2-D amplification for all components within the whole frequency range. Contrastingly, the 1-D amplification differs completely from the other two for the vertical component and remains at the same amplitude level for the horizontal components, also the shape of the spectral amplification is different. At site LEP, on the same section, the theoretical 2-D is very similar with the experimental one for both horizontal components, while the 1-D estimate has approximately a three times lower amplitude in the E-W component. For the vertical component at site LEP, only the theoretical estimation of the amplification is given because there were no recordings available.

Similar results are also obtained at site OTE on section BB (Fig. 2a). The ratios of the N-S component vary at the same amplitude level up to approximately 4 Hz, whereas for higher frequencies the amplitude of the experimental amplification is definitely higher. In the E-W component the 2-D theoretical and the experimental amplifications almost coincide for frequencies higher than 1.5 Hz, whereas the 1-D


Section AA
Station ROT
Section AA
Station LEP
Section BB
Station OTE
Section CC
Station TYF
1D theoretical
2D theoretical
experimental
N-S
E-W
Z
Spectral Ratio
Frequency (Hz)

amplification is underestimated especially for frequencies between 2 and 4 Hz. Finally, for the vertical component there is sufficient agreement between theoretical 2-D and experimental amplifications, with a slight overestimation for the amplitudes of the theoretical ones in all the considered frequency range. On the contrary, the 1-D amplification shows discrepancies with the other two both in amplitudes as well as in the spectral shape.

At site TYF on section CC (Fig. 2a), the three ratios coincide for the E-W component and a very good agreement of the theoretical 2-D and experimental amplification for the N-S component is seen up to approximately 4.5 Hz. The ratios manifest a sufficient agreement for the vertical component up to 3.5 Hz, with a clear underestimation of the experimental amplification for higher frequencies, whereas the 1-D ratio remains totally different. At the sites located along section A2 (Fig. 2b) the primary discrepancies among the three ratios are seen for all components. At site AMP there is a relative agreement between the experimental and the 2-D ratio for all components and frequencies higher than 2 Hz, whereas for lower frequencies all horizontal component ratios differ significantly in shape as well as in amplitudes. Moreover, differences in the ratios appear at site OTE (Fig. 2b), except for the E-W component at frequencies above 2 Hz.

For site LEP (Fig. 2b) there are no experimental data available and therefore only the theoretical estimation of the amplification is given, with only slight differences between 1-D and 2-D ratios. At site TYF (Fig. 2b) the image is like the one at OTE, i.e., good agreement of the three ratios for the E-W component for frequencies higher than 2 Hz, whereas for other components the experimental ratio is obviously overestimated when compared to the theoretical one. It is quite probable that the disagreements observed at most sites of section A2 are due to a non-realistic 2-D design profile, as well as to the simulated event (#4, Table 1, PART-I), which is located at an epicentral distance less than 16 km. Such short epicentral distances can be critical for the application of the hybrid method, because they do not leave enough space for an efficient absorbing zone (FÄH, 1992) leading to the generation of fake reflections at the distant boundary of the 2-D local model, which partly distort the calculated seismograms.

Section A3 has the largest number of comparable instrumented sites and therefore the results at these sites lead to a reliable control of the theoretical methods, as well as of the parameters selected for the simulations. Generally, the three ratios present the same spectral shape and vary at similar amplification levels. Exceptions are the 1-D ratios of E-W components (for frequencies lower than 2.5 Hz) at sites

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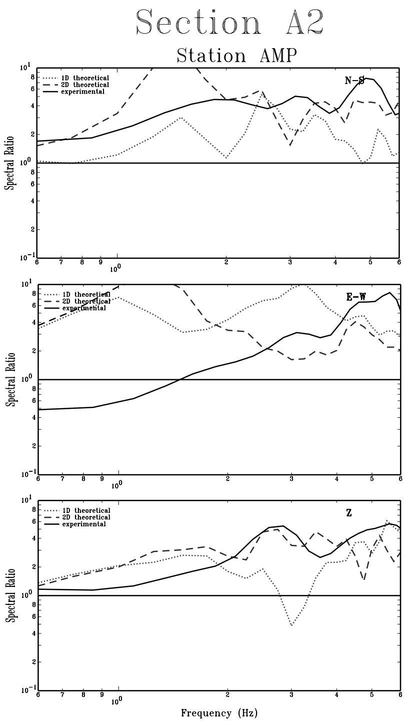
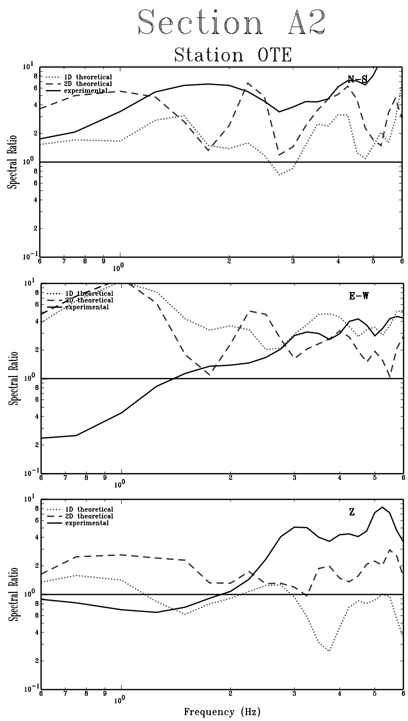
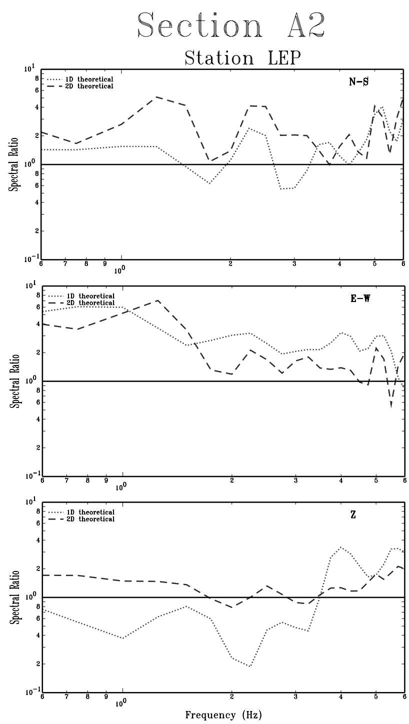
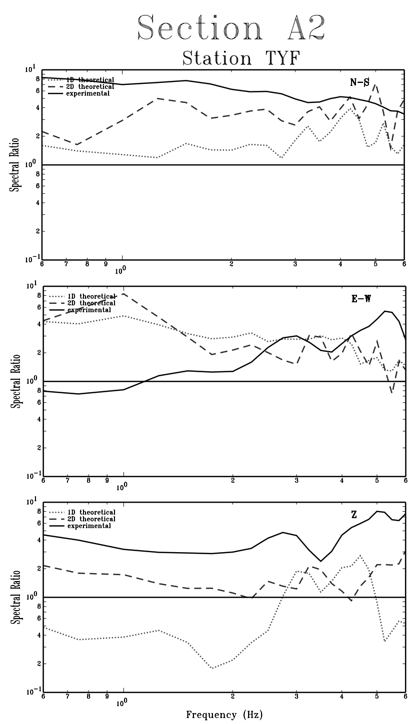
Figure 2a

Comparison of seismic motion amplification obtained from experimental SSR (continuous line) with the theoretical amplifications which resulted from 2-D theoretical (dashed line) and the 1-D simulation (dotted line) at recording sites along sections AA, BB and CC. The comparison is made for the N-S (up), E-W (middle) and vertical (bottom) components.


Section A2
Station AMP
1D theoretical
2D theoretical
experimental
N–S
E–W
Z
Spectral Ratio
Frequency (Hz)


Section A2
Station OTE
1D theoretical
2D theoretical
experimental
N–S
E–W
Z
Spectral Ratio
Frequency (Hz)


Section A2
Station LEP
1D theoretical
2D theoretical
N–S
E–W
Z
Spectral Ratio
Frequency (Hz)


Section A2
Station TYF
1D theoretical
2D theoretical
experimental
N–S
E–W
Z
Spectral Ratio
Frequency (Hz)

ROT (Fig. 2c), POL and KAL (Fig. 2d). At the other sites, AGO, TYF, LEP (Fig. 2c) and POL, the amplification for the 2-D velocity model is in good agreement with the experimental one, while the 1-D amplification is also most often in good agreement with the other two.

Comparison between the Theoretical and Experimental Strong Motion Amplifications due to the 1978, July 4th Earthquake ($M_s = 5.1$)

At site CIT on section A4, digitized signals obtained by an analogue SMA-1 accelerograph are available (CARYDIS *et al.*, 1983). The instrument was triggered by the biggest aftershock (July 4th, $M_s = 5.1$) of the seismic sequence initiated by the strong earthquake, which hit the city of Thessaloniki in 1978 (June 21st, $M_s = 6.5$). The same earthquake also triggered the instrument at site OBS (PETROVSKI and NAUMOVSKI, 1979). This allowed the estimation of the amplification at site CIT by the SSR method with respect to station OBS. Figure 3 displays the recordings of the strong aftershock of July 4th, 1978 at site CIT (left) and site OBS (right), which were used in the computation of the experimental amplification through the application of SSR. For each component the value of PGA is given in $cm \cdot sec^{-2}$. In the last graph of Figure 2d the experimental amplification obtained from the simulation of this earthquake by applying the SSR method is compared to the theoretical one obtained from the hybrid and modal summation methods in local 2-D and 1-D models, respectively, of site OBS. The very good agreement in amplification of the experimental data and the theoretical 2-D model is obvious for the two horizontal components over the entire frequency range. The 1-D amplification differs from the previous two for frequencies above 4 Hz, yielding relatively higher values. The similarity of the experimental ratio with the theoretical 2-D one refers not only to the same amplitude level, but also to the spectral shape of amplification with a matching of troughs and basins within the complete frequency band. This is not observed for the vertical component, for which we observe a shifting of troughs of 0.5–1 Hz, whereas the amplitude of the two curves lies at the similar level. At site AGO only the theoretical estimation of the amplification can be made, due to lack of experimental records from the simulated earthquake.

From the above Figures 2 and 3, the success of the theoretical 2-D simulations to estimate the amplification of each site, giving with sufficient detail its expected amplitude and in most cases the fundamental frequency, is quite obvious. Moreover, the amplifications obtained from theoretical 1-D simulations, may contribute only to

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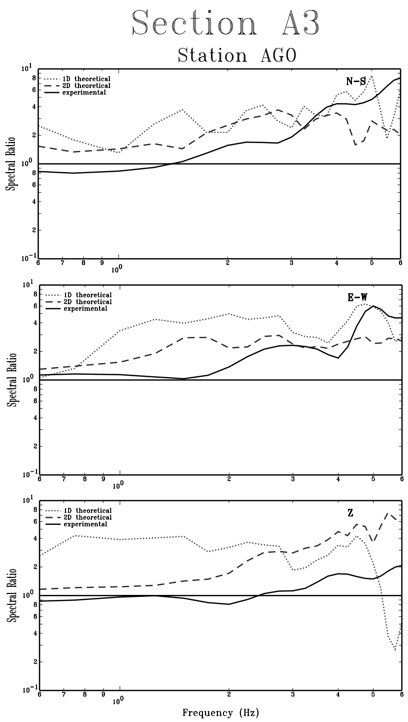
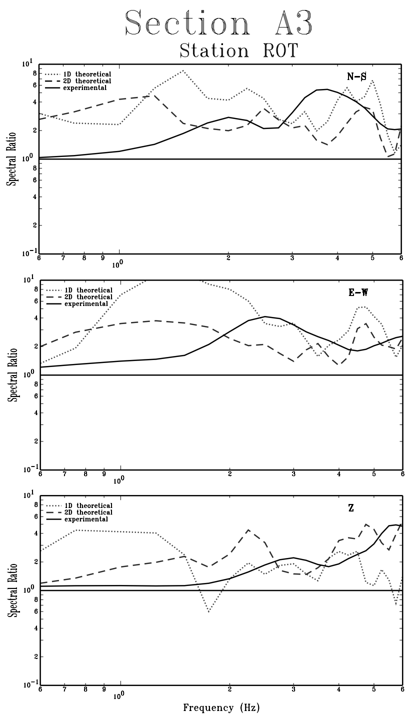
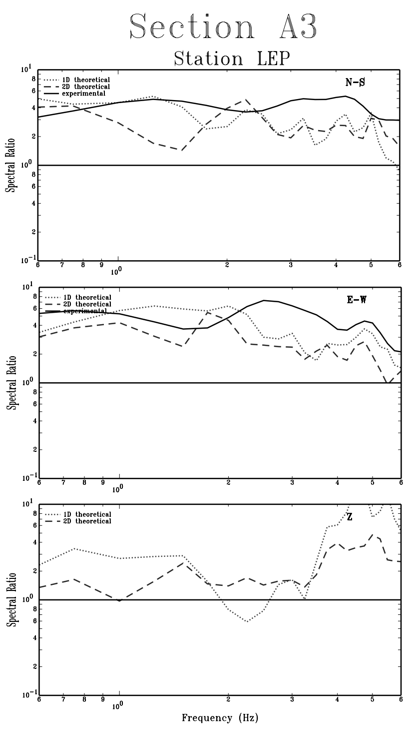
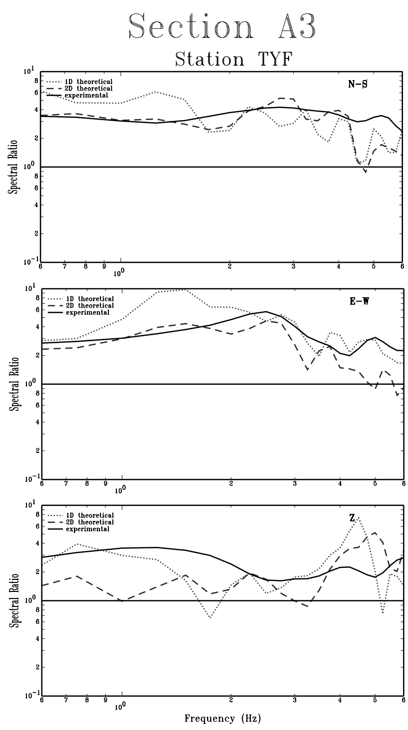
Figure 2b
The same as Figure 2a but for section A2.


Section A3
Station AGO
1D theoretical
2D theoretical
experimental
N–S
E–W
Z
Spectral Ratio
Frequency (Hz)


Section A3
Station ROT
1D theoretical
2D theoretical
experimental
N–S
E–W
Z
Spectral Ratio
Frequency (Hz)


Section A3
Station LEP
1D theoretical
2D theoretical
experimental
N–S
E–W
Z
Spectral Ratio
Frequency (Hz)


Section A3
Station TYF
1D theoretical
2D theoretical
experimental
N–S
E–W
Z
Spectral Ratio
Frequency (Hz)

a first-order estimation of amplitudes and fundamental frequencies, particularly for the horizontal components.

Discussion

Although the comparison between the amplifications emanating the experimental techniques and those estimated theoretically with the hybrid method is very satisfactory, in some sites certain discordances have been observed, concerning the amplification amplitudes and the spectral ratio shape. This misfit between the theoretical and experimental curves is particularly evident for frequencies above 4 Hz and makes the theoretical results meaningful only for lower frequencies. Possible reasons for such discordances are the scattering effect and the influence of the 3-D geometry for a specific frequency window. This is quite evident when the level of the estimated amplification is different for each (horizontal) component.

Another reason could be the fact that the receivers of the experimental measurements were not located exactly over the examined section and only their vertical structure was projected on it. That is why the positions of the real and synthetic receivers are not always coincident and the geological-geotechnical conditions may differ from those which were initially used as input data.

The differences between the focal mechanisms of the simulated earthquakes and the earthquake recorded during the experiment may also be a cause of disagreement. Apart from the 1978 earthquakes of Thessaloniki (#1, #5, Table 1, PART-I), which were simulated using the 2-D approach, the other focal mechanisms represent the average stress field of the area. Although the use of the average focal mechanism would be essential for a microzonation study, for the case of a future design earthquake in this area, the comparison with the experimental recordings of an earthquake with a different focal mechanism may present certain differences, as already noted by MOLDOVEANU and PANZA (2001).

For this reason and because of the sensitivity of the numerical methods to the variations of source parameters (focal mechanism, depth, source-receiver distance and azimuth) the simulation must always be conducted with the same limitations as those of the observations. More specifically, the calculation of the synthetic waveforms must be made at the same stations (examined site and reference station) where the instrumental observations were recorded. Additionally, the comparison should always be made at the same components (N-S, E-W and vertical) considering the same spectral ratios (synthetic waveforms of the local model to these of the reference station).

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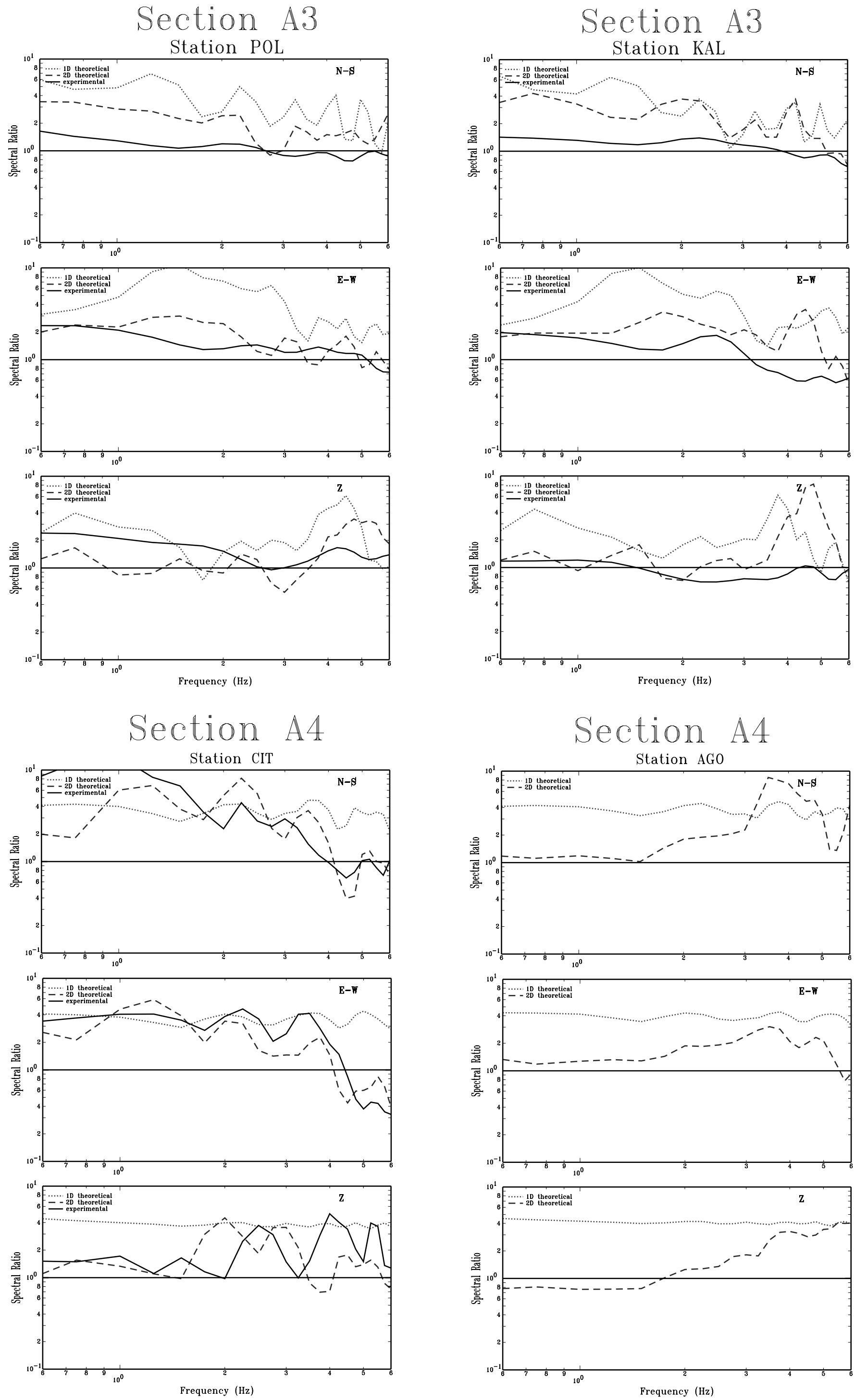
Figure 2c
The same as Figure 2a but for section A3.


Section A3
Station POL
Section A3
Station KAL
Section A4
Station CIT
Section A4
Station AGO
1D theoretical
2D theoretical
experimental
N-S
E-W
Z
Spectral Ratio
Frequency (Hz)

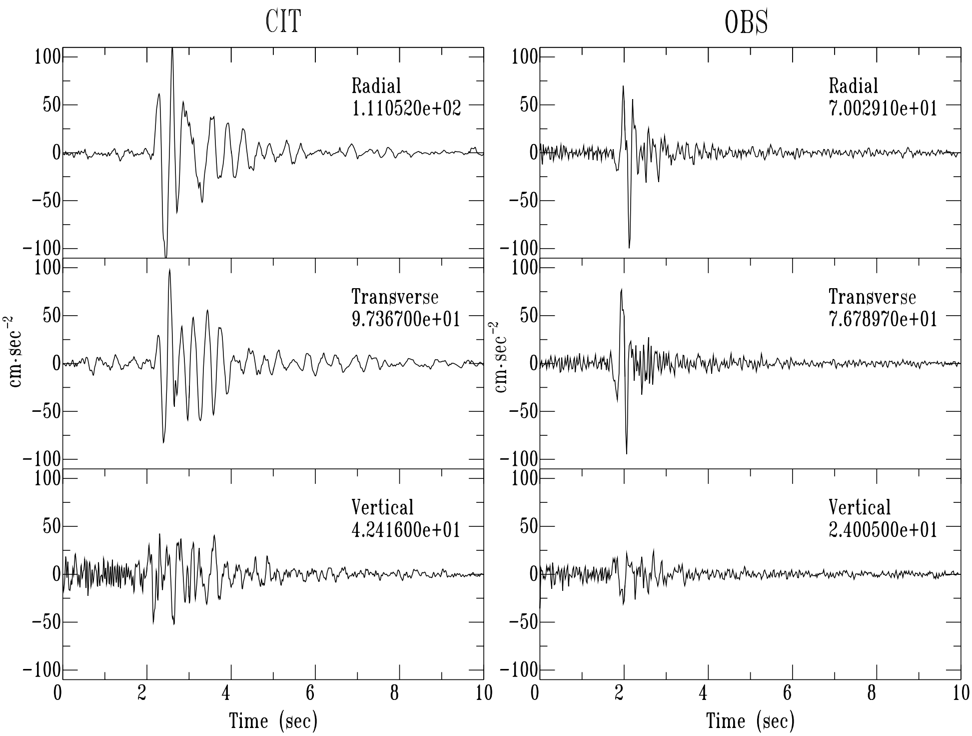


Figure 3
Digitized waveforms of the radial (up), transverse (middle) and vertical (bottom) components of the largest aftershock of the 1978 seismic sequence (July 4, 1978, $M_S = 5.1$) at sites CIT (left) and OBS (right).

For future references or microzonation studies, the site effects could be more accurately estimated (taking the spectral ratios of the corresponding components at the same site) by simulating first the local one- or two-dimensional geometry of the layers at the specific site and the regional one-dimensional afterwards (reference model). In this way, the differences due to the propagation path in the regional bedrock model are eliminated. In the case of contiguous earthquakes, i.e., when the source-station distance is comparable to the distance between the stations, these dissimilarities are particularly intense. They are the result of the difference in distance between the analyzed site and the reference station, as well as of the different azimuth between the source and the two stations.

The hybrid method constitutes a very useful tool which can offer applicative and practical results for regions where the theoretical estimation of the seismic motion

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Figure 2d
The same as Figure 2a but for sections A3 and A4.

amplification is required and detailed geotechnical data are available, especially at regions with no significant seismic activity or densely populated urban areas. The methodology followed in this study provided us with results which could be easily and effectively used in microzonation and seismic hazard reduction studies of the city.

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