Spatial distribution of site effects and wave propagation properties in Thessaloniki (N. Greece) using a 3-D finite difference method

A. A. Skarlatoudis, C. B. Papazachos and N. Theodoulidis

1 Department of Geology, University of Thessaloniki, Thessaloniki, Greece, E-mail: askarlat@geo.auth.gr
2 Institute of Engineering Seismology and Earthquake Engineering, ITSAK, Thessaloniki, Greece

Accepted 2011 January 12. Received 2011 January 12; in original form 2010 April 7

SUMMARY
The detailed wave propagation characteristics and the spatial distribution of site effects in the metropolitan area of Thessaloniki are studied using a 3-D finite-difference method. Fourier amplitude spectra (FAS) and standard spectra ratios (SSR) are computed for various scenarios and their spatial distribution is examined throughout the Thessaloniki metropolitan area, in order to study the spatial variability of site-response. The variability of the contribution of different model layers in site amplification at different frequency windows and the identification of high amplification areas due to the presence of trapped waves in the surficial layers of the model identified along selected cross-sections, verify the impact of the complex 3-D wave propagation on the computed synthetics. Moreover, examination of the spatial distribution of the fundamental period ($T_{SSR}^0$) from synthetic SSR and comparisons with results from ambient noise measurements show that for (thicker soil formations) the average $H/V$ results for the fundamental period from ambient noise measurements, $T_{Noise}^{H/V}$, tend to overestimate (by roughly 30–35 per cent) the average fundamental periods from 3-D synthetics, $T_{3-D}$. The characteristics of the computed time-series and the type and properties of the dominating seismic waves are also examined along the same typical cross-sections spanning the study area, revealing the selective propagation of Love surface waves for various seismic scenarios. The previous results, as well as the strong spatial and interscenario variability of various measures of seismic motion such as Fourier spectra, peak ground velocity, cumulative energy and Housner intensity show a complicated 3-D wave propagation pattern, affecting the final site-effect distribution, both in the time and frequency domain. In most cases, even for areas with relatively simple shallow structure, the final site-response strongly depends on the seismic source characteristics, indicating the necessity of specific earthquake scenario 3-D synthetics for the study of complex 3-D geometry sedimentary basins, such as the broader Thessaloniki region.

Key words: Earthquake ground motions; Site effects; Wave propagation.

1 INTRODUCTION
During the last decades it has become widely accepted that the preventive estimation of local site effects on seismic motions constitutes a powerful tool for efficient seismic risk mitigation in large, densely populated cities. There are several cases of destructive earthquakes over the last years (e.g. Northridge, USA 1994; Kobe, Japan 1995; Athens, Greece 1999) for which a better preventive knowledge of site effects (e.g. Trifunac et al. 1999; Koliopoulos & Margaris 2001; Akiyoshi et al. 2003; among others) could lead to a significant reduction of damage and human losses. site effects estimation is usually based on various types of recordings (e.g. earthquake or ambient noise) or appropriate theoretical modelling.

In this work, a 3-D site-effect study is performed for the city of Thessaloniki with the use of 3-D numerical simulation of wave propagation. The city of Thessaloniki (northern Greece) is located in a moderate-to-high seismicity region (Papazachos et al. 1983), with the Servomacedonian massif and N. Aegean trough areas exhibiting the highest seismicity (Fig. 1). The city suffered several large earthquakes throughout its history, many of them causing significant damage and human losses (Papazachos & Papazachou 2002). The most recent earthquake with significant impact on the city occurred in the late seventies (1978 June 20, M6.5), with strong spatial variation of the resulting damage, especially along the coastal zone (Carydis et al. 1983; Papazachos et al. 1983; Tsotsos & Zissis-Tegos 1986). As a result, several researchers performed various studies of the site-effect contribution on ground motion and structural behavior prediction during strong earthquakes. These studies were either experimental (Scherbaum et al. 2002; Leventakis 2003; Apostolidis et al. 2004a,b; Panou et al. 2005a,b; among others).
or numerical (e.g. Triantafyllidis et al. 1998, 1999, 2004a,b; Raptakis et al. 1998, 2004a,b), mainly based on 1-D or 2-D simulations of seismic motion. Recently, Skarlatoudis et al. (2010), using a 3-D finite-difference (FD) scheme for the broader area of Thessaloniki, showed that for several selected sites the previous 1-D and 2-D simulations could not adequately describe the site-response, in comparison with the 3-D wave propagation results.

This study extends the results of Skarlatoudis et al. (2010) by examining the spatial variation of ground motion characteristics for the city of Thessaloniki both in the time and frequency domain by using appropriate measures for the estimation of site-response such as spectral ratio, peak ground velocity (PGV), cumulative energy (Olsen et al. 1995) and Housner intensity (Housner 1952). Time–frequency analysis of the synthetic waveforms along selected cross-sections is also performed, in order to study the generation and propagation of surface waves. Moreover, the spatial variability of the fundamental frequency, $f_0$ is estimated for various seismic scenarios and comparisons with results estimated from $H/V$ ratios of ambient noise measurements (Panou et al. 2005b) are also presented. The study of the spatial distribution of the various measures used for site-response evaluation, together with comparisons performed with 2-D synthetics from other researchers are used to further check and validate the reliability of the theoretically estimated ground responses, in order to produce a detailed image of the spatial distribution of site effects and provide a sufficient explanation on the ground motion variability observed in the complex-geometry sedimentary basin of Thessaloniki.

2 COMPUTATIONAL METHOD AND MODEL

An explicit 3-D fourth-order velocity–stress FD scheme with discontinuous spatial grid was used for the numerical simulations. The scheme solves the equation of motion and Hooke’s law for viscoelastic medium with rheology described by the generalized Maxwell body model,

$$\rho v_t = \sigma_{ij,j} + f_i$$

and

$$\sigma_{ij} = \kappa \dot{\varepsilon}_{kk} \delta_{ij} + 2\mu \left( \dot{\varepsilon}_{ij} - \frac{1}{3} \delta_{kk} \dot{\varepsilon}_{ij} \right) - \sum_l \left[ \kappa I_l^{\nu} \xi_l^{\nu} \delta_{ij} + 2\mu I_l^{\mu} \left( \xi_l^{\mu} - \frac{1}{3} \xi_l^{kk} \delta_{ij} \right) \right],$$

$$\dot{\xi}_l^{\mu} + \omega_l \xi_l^{\mu} = \omega_l \dot{\varepsilon}_{ij}; \quad l = 1, \ldots, 4.$$
where \( \omega \), \( \theta \) controls the width of the signal and \( \gamma \) finally adopted for the source–time function parameters are provided by Moczo et al. (2002), Kristek & Moczo (2003), Moczo & Kristek (2005), Moczo et al. (2007) and Kristek et al. (2009b). Adjusted fourth-order accurate FD approximations are applied at the planar free surface (Kristek et al. 2002; Moczo et al. 2004), while the unsplit PML formulation is used to prevent spurious reflections from the boundaries of the grid (Skarlatoudis et al. 2006; Kristek et al. 2009a). Since the hypocentres of the earthquakes that are later simulated in the examined scenarios are located sufficiently far from the receivers and the magnitude of the simulated earthquakes is relatively small (\( M_{S}1 \)), a double-couple point source was assumed for each earthquake. For the source–time function, representing particle velocity, a bandlimited Gabor signal was adopted, of the form:

\[
s(t) = \exp \left\{ -[\omega (t - t_s) / \gamma]^2 \right\} \cos [\omega (t - t_s) + \theta],
\]

where \( \omega = 2\pi f_p \), \( t \in [0, 2t_s] \), \( f_p \) is the dominant frequency, \( \gamma \) controls the width of the signal and \( \theta \) is the phase shift. The values finally adopted for the source–time function parameters are \( \gamma = 0.25 \), \( f_p = 0.2 \), \( \theta = \pi/2 \) and \( t_s = 1.0 \), corresponding to a dominant frequency band between 0.2 and 3 Hz.

The computational model used for the simulations is based on the geophysical–geotechnical model and the dynamic characteristics of the soil formations proposed by Anastasiadis et al. (2001). The main soil information, such as dynamic properties and ages for each formation are shown in Table 1. The original coverage of the model was extrapolated to cover the whole study area (denoted hereinafter as AN01 modified model) using mainly information (thickness and geometry of formations) from the model of Apostolidis et al. (2004b) in areas where the AN01 model provided little or no information (e.g. western and eastern parts of the city of Thessaloniki), covering the area of \( 9 \times 12 \) km\(^2\) shown in Fig. 2 (white dashed line) and in Fig. 3 (black solid line). Towards the NE direction the dominating formation of the model is the bedrock (mainly gneiss), with a surface manifestation throughout the largest part of this area, thus in the extrapolation procedure the presence of the bedrock formation for the whole N–NE area was adopted. The proposed extrapolation approach of the model towards the W–SW direction was performed taking into account the continuous thickening of the Neogene sedimentary formations towards that direction (Fig. 4), as delineated by the results from Lalechos & Savoyat (1979), also presented in Fig. 1. Detailed information on extrapolation procedure and the geometry of the main soil formations of the modified AN01 geophysical–geotechnical modified model are provided in Skarlatoudis et al. (2010). The final computational model, produced by extrapolating the modified AN01 in order to include the earthquake hypocentres, covers an area of \( 22 \times 16 \) km\(^2\). It should be noted that the lowest theoretical frequency for which the

<table>
<thead>
<tr>
<th>Formation</th>
<th>Description</th>
<th>Age</th>
<th>( \alpha ) (m s(^{-1}))</th>
<th>( \beta ) (m s(^{-1}))</th>
<th>( \rho ) (kg m(^{-3}))</th>
<th>( Q_\alpha )</th>
<th>( Q_\beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Artificial fills, Demolition materials &amp; debris parts</td>
<td>Anthropogenic layer</td>
<td>1050</td>
<td>250</td>
<td>2.050</td>
<td>260</td>
<td>15</td>
</tr>
<tr>
<td>B</td>
<td>Very stiff sandy-silty clays to clayey sands, low plasticity, soft sandy-silty clays to clayey sands low to medium plasticity, stiff to hard high plasticity clays</td>
<td>Quaternary–Upper Pliocene</td>
<td>1850</td>
<td>180</td>
<td>2.300</td>
<td>1130</td>
<td>25</td>
</tr>
<tr>
<td>C</td>
<td>Very soft bay mud &amp; silty sands</td>
<td>Quaternary</td>
<td>1900</td>
<td>300</td>
<td>2.150</td>
<td>510</td>
<td>20</td>
</tr>
<tr>
<td>E/F</td>
<td>Stiff to hard sandy-silty clays to clayey sands very stiff to hard low to medium plasticity clays to sandy clays over consolidated with rubble and thin layers of gravels</td>
<td>Neogene (mainly Lower Pliocene–Upper Miocene)</td>
<td>3000</td>
<td>700</td>
<td>2.350</td>
<td>690</td>
<td>50</td>
</tr>
<tr>
<td>Bedrock(at free surface)</td>
<td>GreenSchists &amp; Gneiss</td>
<td>Mesozoic (upper triassic)</td>
<td>4500</td>
<td>2000</td>
<td>2.600</td>
<td>450</td>
<td>200</td>
</tr>
<tr>
<td>Bedrock(1000 m)</td>
<td>GreenSchists &amp; Gneiss</td>
<td></td>
<td>6000</td>
<td>3400</td>
<td>2.600</td>
<td>450</td>
<td>200</td>
</tr>
</tbody>
</table>

Details on the scheme, its grid and material parametrization are provided by Moczo et al. (2002), Kristek & Moczo (2003), Moczo & Kristek (2005), Moczo et al. (2007) and Kristek et al. (2009b).
synthetic waveforms were produced for a coarse grid of receivers, in order to study the spatial variation of site effects on seismic motion in the broader metropolitan area of Thessaloniki (Fig. 3). Additional computations were performed for a dense grid, covering the historical centre of the city of Thessaloniki. Moreover, synthetic waveforms were also computed for 11 selected sites in the broader area of Thessaloniki (Fig. 4a), for which seismic records were available from a local network of seismographs and accelerographs, operated for as period of 4 months (1993 November–1994 February, Lachet et al. 1996).

3 Comparisons in Frequency Domain

The synthetics computed for the six seismic scenarios were compared along three cross-sections shown in the map of Fig. 4(a) (red, green and purple lines) with the corresponding 2-D results of Triantafyllidis et al. (2004a) and Raptakis et al. (2004b). The Fourier amplitude spectra (FAS) ratio for the 3-D over the corresponding 1-D bedrock reference model ([FAS3D]/[FAS1D]) was estimated for a large number of receivers along the cross-sections for all scenarios and components of ground motion. In all plots and comparisons we employ both horizontal components, instead of a single, for example, orientation-independent measure of seismic motion. This preference was mainly based on the necessity to study certain aspects of the physics of the wave propagation (e.g. identification of surface waves for certain scenarios and receivers), which would not always be possible when using a combined single measure of seismic motion. Furthermore, all 1-D and 2-D results previously published for the city of Thessaloniki also employed both horizontal components; hence comparisons with existing but also future studies could only be realized by presenting both horizontal components.

As most of the comparisons that follow are presented as 3-D/1-D ratios, it was necessary to examine the agreement level of 3-D and 1-D simulations at the selected rock (reference) sites. Comparisons performed for all six scenarios, both in time and frequency domain (corresponding figures for scenarios (1a) and (1b) are given in Fig. S1(a), showed that 3-D and 1-D synthetics, for the reference site OBS (also used in earlier studies) are practically identical, hence the obtained results are not affected by the adopted numerical model/method at the selected reference site (OBS).

Results from Triantafyllidis et al. (2004a), produced with a hybrid method (Fah 1992), are presented in the form of Pseudo-spectral Acceleration ratios ([PSA2D]/[PSA1D]). The use of the ([PSA3D]/[PSA1D]) ratio, computed from PSA records for 5 per cent damping, was also initially employed in this study, however, comparisons (not shown here) between ([FAS3D]/[FAS1D]) and ([PSA3D]/[PSA1D]) ratios exhibit almost identical spatial variation and only small differences of the predicted ratios. Taking into account that FAS directly describe the spectral characteristics of ground motion (rather than the indirect nature of PSA), the ([FAS3D]/[FAS1D]) ratio was finally employed for studying the site-amplification characteristics throughout the study area.

To facilitate the correlation of site-amplification characteristics with the local structure, the variation of the bedrock depth (controlling the fundamental frequency) and the recent soft-soil sedimentary cover thickness (anthropogenic and mostly Quaternary/Upper Pliocene formations—types A, B and C in Table 1) are also presented in Fig. 4(a). ([FAS3D]/[FAS1D]) ratios were examined for three typical cross-sections, spanning the examined
Distribution of site effects in Thessaloniki

Figure 4. (a) Left-hand panel: bedrock depth for the modified AN01 geophysical–geotechnical model. Recording sites from the Lachet et al. (1996) experiment for which earthquake recordings were available and the cross-sections studied in this work spanning the metropolitan area of Thessaloniki are also shown. The AMP-LAB section is denoted with the magenta colour, AGK-KAL and LEP-OBS sections denoted with the green and red colour, corresponding to cross-sections A3 and AA of Triantafyllidis et al. (2004b). Receiver R1 for AGK-KAL cross-section is shown with the black square, respectively. Right-hand panel: thickness of anthropogenic and recent (mostly Quaternary and upper Pliocene) soft-soil sedimentary formations (formations A, B, C in Table 1) of the same model. (b) Structure of the model formations along the AMP-LAB (magenta), AGK-KAL (green) and LEP-OBS (red) cross-sections. Blow-up of the top structure for the AMP-LAB and AGK-KAL (30 m) and of LEP-OBS (20 m) cross-sections, depicted with the black dashed lines in the bottom figures, are also presented in the top figures.

area (Fig. 4a), while the corresponding model formations along these cross-sections are presented in Fig. 4(b). The frequency variation of \([FAS3D]/[FAS1D]\) ratio along the cross-sections LEP-OBS (red), AGK-KAL (green) and AMP-LAB (purple) is presented in Figs 5–7, where scenarios (1), (2) and (3) are plotted from left to right and the N–S, E–W and vertical components are shown from top to bottom, respectively.

As also previously mentioned, despite the ‘strict’ limit imposed for the highest frequency for which computations can be considered as theoretically accurate (2 Hz), results for Figs 5–7 are presented up to the frequency of 5 Hz. The assumption that computations can perform for frequencies higher than the theoretical limit, is mainly based on the comparisons presented in Skarlatoudis et al. (2010) in the frequency domain, using both empirical and synthetic data. These comparisons showed that although the simulations were theoretically accurate up to the frequency of 2 Hz, the obtained results could perform accurately to much higher frequencies, up to \(\sim \)5 Hz. Specifically, SSR results showed that the simulations can predict up to \(\sim \)5 Hz with sufficient accuracy both the fundamental frequency and the amplitude levels, as these were estimated from empirical data from both velocimeters and accelerometers. On the other hand, the comparison of 3-D simulations with the available results from 1-D and 2-D simulations (estimated with various methods) which were theoretically accurate for frequencies considerably higher than the theoretical 2 Hz limit of the 3-D simulations (typically up to the frequency of 10 Hz) showed that the 3-D simulations perform much better than the 1-D and 2-D ones both in terms of fundamental frequency and amplitude for frequencies up to \(\sim \)5 Hz.

In order to further justify the previous assumption we have computed synthetics theoretically accurate up to the frequency of 3 Hz and performed comparisons with present study results (theoretically accurate up to the frequency of 2 Hz) both in the frequency and time domain for a typical scenario (scenario 1a). Comparisons were performed mostly for sites either residing or with significant thickness of formation B (see Table 1), which exhibits the lowest S-wave velocity, as synthetics should be mostly affected for such sites as a result of the reduced spatial sampling. The results (presented in Figs S1b and c) showed that for frequencies up to \(\sim \)5 Hz the differences between the two computations are practically very small or even negligible in terms of peak values and duration of
Table 2. Computational model parameters.

| Model dimensions: $X = 22545$ m, $Y = 16200$ m, $Z = 12105$ m |
| Grid spacing: 15 m in the finer grid (0–1170 m), 135 m in the coarser grid |
| Number of grid cells: $(1503 \times 1080 \times 78) + (167 \times 120 \times 81) = 128\,235\,960$ |
| Frequency range: 0.2–2.0 Hz |
| Time step: 0.0012 s |
| Time window: 20 s |
| PML zone thickness: 90 grid spacings in the finer grid 10 grid spacings in the coarser grid |

Table 3. Focal parameters of the earthquakes used for the computation of synthetic waveforms. All earthquakes have the same moment magnitude ($M_5.1$) and focal depth (5 km), except when otherwise specified in the text.

<table>
<thead>
<tr>
<th>A/A</th>
<th>Lon (E)</th>
<th>Lat (N)</th>
<th>Strike</th>
<th>Dip</th>
<th>Rake</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>23.0743</td>
<td>40.7506</td>
<td>90</td>
<td>55</td>
<td>–70</td>
</tr>
<tr>
<td>1b</td>
<td>23.0743</td>
<td>40.7506</td>
<td>135</td>
<td>55</td>
<td>–90</td>
</tr>
<tr>
<td>2a</td>
<td>23.0743</td>
<td>40.5977</td>
<td>90</td>
<td>55</td>
<td>–70</td>
</tr>
<tr>
<td>2b</td>
<td>23.0743</td>
<td>40.5977</td>
<td>135</td>
<td>55</td>
<td>–90</td>
</tr>
<tr>
<td>3a</td>
<td>22.9295</td>
<td>40.7506</td>
<td>90</td>
<td>55</td>
<td>–70</td>
</tr>
<tr>
<td>3b</td>
<td>22.9295</td>
<td>40.7506</td>
<td>135</td>
<td>55</td>
<td>–90</td>
</tr>
</tbody>
</table>

Strong-motion, as well as regarding their corresponding frequency content, for all the sites studied, verifying the robustness of the presented synthetics in this study.

For the LEP-OBS cross-section (Fig. 5) one of the most prominent features is the existence of two distinct high-amplification zones (spectral amplifications ranging from 5 to 15) in both horizontal components for the majority of the examined scenarios. This feature is mostly evident in scenarios (a) (E–W trending faults), with the manifestation of a first zone of higher amplitudes followed at lower frequencies by a second zone with slightly lower amplification amplitudes, which corresponds to the fundamental frequency of the sediment–bedrock interface. Nevertheless, in scenarios (b) (NW–SE trending faults) this pattern is not so clear and in some cases [scenario (3b) and north–south component of scenario (1b)] is practically absent. The two distinct amplification bands correspond to the contribution of different model layers in site amplification, at different frequency windows along the cross-section. The fact that they are not identified in all scenarios and ground motion components is strong evidence of the impact of the combined effect of source and 3-D geometry of the Thessaloniki sedimentary basin geophysical model on the final site effects. It should be noted that all vertical components do not exhibit noticeable amplifications, with their values varying mostly between 1 and 2 in most cases.

The amplification of trapped waves in the surficial layers of the model may be a reasonable explanation for the high amplitude areas observed in the AGK-KAL cross-section, shown in Fig. 6. These high amplitude areas around 2 Hz (Maximum FAS ratio amplitudes ranging from 7 to 15) are mostly prominent in the north–south components, for almost all scenarios. Nevertheless, they are not identified as clearly for scenario (2b). Moreover, a second zone of relatively smaller amplifications (up to 7–8), can be identified around the frequency of 1 Hz, for almost all scenarios and components of ground motion and is the manifestation of the effect of the bedrock–sediments discontinuity on the spectral ratios. Significant differences in the amplifications are observed between scenarios (1) (in both horizontal components) and scenarios (3) (mostly in the E–W component) for the frequency range of ~1–4 Hz. Finally, similar to the LEP-OBS cross-section, the bedrock geometry is quite clearly reflected in the FAS ratio distribution. For the vertical
Figure 5. (a) Frequency variation of $(FAS3D)/(FAS1D)$ ratio along the LEP-OBS cross-section. Starting from left, scenarios (1a), (2a) and (3a) are shown, respectively. From top to bottom, results for the N–S, E–W and vertical components are plotted. The structure of the model formations along the cross-section is presented in Fig. 4(b). (b) Frequency variation of $(FAS3D)/(FAS1D)$ ratio along the LEP-OBS cross-section. Starting from left, scenarios (1b), (2b) and (3b) are shown, respectively. From top to bottom, results for the N–S, E–W and vertical components are plotted. The structure of the model formations along the cross-section is presented in Fig. 4(b).
Figure 6. (a) Frequency variation of \((FAS3D)/(FAS1D)\) ratio along the AGK-KAL cross-section. Starting from left, scenarios (1a), (2a) and (3a) are shown, respectively. From top to bottom, results for the N–S, E–W and vertical components are plotted. The structure of the model formations along the cross-section is presented in Fig. 4(b). (b) Frequency variation of \((FAS3D)/(FAS1D)\) ratio along the AGK-KAL cross-section. Starting from left, scenarios (1b), (2b) and (3b) are shown, respectively. From top to bottom, results for the N–S, E–W and vertical components are plotted. The structure of the model formations along the cross-section is presented in Fig. 4(b).
Figure 6. (Continued.)
Figure 7. (a) Frequency variation of (FAS3D)/(FAS1D) ratio along the AMP-LAB cross-section. Starting from left, scenarios (1a), (2a) and (3a) are shown, respectively. From top to bottom, results for the N–S, E–W and vertical components are plotted. The structure of the model formations along the cross-section is presented in Fig. 4(b). (b) Frequency variation of (FAS3D)/(FAS1D) ratio along the AMP-LAB cross-section. Starting from left, scenarios (1b), (2b) and (3b) are shown, respectively. From top to bottom, results for the N–S, E–W and vertical components are plotted. The structure of the model formations along the cross-section is presented in Fig. 4(b).
Figure 7. (Continued.)
components of ground motion, strong amplifications (locally up to 8) are surprisingly found for scenarios (1) around the frequency of 1 Hz, however this is the only case for which such high values of amplification are observed for the vertical component.

For the third cross-section studied, AMP-LAB (Fig. 7), the highest amplifications are identified at the edges of the cross-section, around sites AMP and LAB, where the deeper sedimentary deposit structures are located. The most prominent differences regarding FAS amplitudes between scenarios can be observed for scenarios (1) and (3), where for the former higher amplifications are exhibited in scenario (1b) [in the north–south component of scenario (1a), only the neighbourhood around station AMP exhibits high amplifications] while for the latter, high amplifications are alternating between the two amplification ‘lobes’ formed close to sites AMP and LAB. The effect of the bedrock geometry is not clearly identified in all components of ground motion for the six scenarios studied, which is indicative of the different site response due to excitation by difference seismic sources. Vertical components also show minimal amplification levels for all six scenarios examined.

Triantafyllidis et al. (2004a) compared theoretical and experimental estimations of site effects using 2-D numerical simulations and studied the frequency variation of spectral acceleration response ratios SA(2-D/1-D), which are presented in Fig. 8 for the same cross-sections of this study, namely AA(LEP-OBS), A3(AGK-KAL) and A5(AMP-LAB). In these 2-D simulations, both the receivers and the corresponding seismic source were located along the cross-section, hence it is not possible to perform a direct comparison with present study results. However, this source–receiver alignment condition is approximately valid for scenarios (1a)/(1b) and the AA(LEP-OBS) cross-section, as well as for scenario (3a)/(3b) and A3(AGK-KAL) cross-section. Using these sections and scenarios, comparisons between the general characteristics of the spectral amplifications computed for each cross-section can be performed, in order to reveal the main differences between 2-D and 3-D numerical modelling for the specific area.

Comparison for the AA(LEP-OBS) cross-section shows that amplifications from 3-D synthetics for the central part of the cross-section (where deeper sedimentary formations are found) are significantly higher for higher frequencies (> 2.5 Hz). Moreover, the two distinct high-amplification zones observed in most of the scenarios studied could not be identified in the results of Triantafyllidis et al. (2004a), even for scenarios (1a) and (1b) where the source used in this study lies almost along the profile, similar to the 2-D synthetics. For cross-section A3(AGK-KAL) this study results show more clearly the high amplification zone, as well as the bedrock geometry impact on site amplification. In addition the high amplification area in the vicinity of the AGK site, spanning the whole upper frequency range studied (1–5 Hz) and controlled by the bedrock–sediments discontinuity is almost not identified in results of Triantafyllidis et al. (2004a). Finally, the 0.5–2 Hz amplification zone observed in the radial component of section A3 is in a good agreement with results from scenario (3a; north–south component).

The results for cross-section A5(AMP-LAB) show a similarly good qualitative agreement with the ones of Triantafyllidis et al. (2004a). The high amplification areas observed in the neighborhood of sites AMP and LAB can be identified in the results of both studies (Figs 7 and 8). However, 2-D results do not predict such high values of amplification in the area of site AMP, unlike results presented in Figs 7, which exhibit very high amplifications in both horizontal components of ground motion [e.g. scenario (1b)].

Qualitative comparisons are also shown with 2-D synthetics obtained by Raptakis et al. (2004b) for the LEP-OBS cross-section. In Fig. 9 the theoretical transfer function for vertical incidence SH waves, normalized over the corresponding bedrock model (unity in the absence of sediment layers) is shown. In general the comparisons show an adequate qualitative agreement with this study results in terms of the amplification level predicted and the effect of the bedrock–sediments discontinuity. However, for the frequency range of 2–5 Hz and for distances up to 1000 m, Raptakis et al. (2004b) predict much lower amplification amplitudes than the ones shown in Fig. 5.

4 SPATIAL DISTRIBUTION OF FUNDAMENTAL FREQUENCY $f_0$ AND PERIOD $T_0$

One of the most popular measures for characterizing site response is the fundamental frequency, $f_0$. In order to map the spatial variability of site-response in the study area, $f_0$ values were estimated from SSR, for a coarser and a denser grid of receivers (Fig. 3) and four seismic scenarios (1a, 1b, 2a and 3a). Station OBS, which is located on bedrock (shown in Fig. 3 with a yellow triangle), was used as a reference site, in accordance with previous studies employing either real or synthetic recordings for the city of Thessaloniki (e.g. Lachet et al. 1996; Raptakis et al. 2004b; Triantafyllidis et al. 2004a; Skarlatoudis et al. 2010). In Fig. 10 the corresponding maps of $f_0$, spatial distribution are presented. White areas correspond to sites, for which the fundamental frequency is higher than the practically accurate maximum frequency (5 Hz) for the FD modelling employed. Nevertheless, as it can be seen in Fig. 10, the vast majority of the estimated $f_0$ values are within the frequency band of 0.3–5 Hz. In the inset maps the epicentre and the focal mechanism of each earthquake scenario are presented.

The results of Fig. 10 verify the variability observed in the ground motion responses by Skarlatoudis et al. (2010), as the $f_0$ values depend not only on the local structure but also on the source properties (source position and focal mechanism). This variability is also evident in scenarios (1a) and (1b), where the only change is the different focal mechanism used in the simulations, yet the soil responses are locally quite different. The most prominent differences are noticed in the historical centre of Thessaloniki (grey shaded area in Fig. 10a), where higher $f_0$ values are found for larger parts of the study area in scenario (1b). The differences in site response between scenarios (1a) and (1b) are most probably controlled by the different contribution of each soil formation in the amplification process when triggered by different seismic excitations. Thus, the observed site-response of a specific site can also vary depending on the properties of the seismic source used for exciting the soil formations. Differences are also noticed for scenarios (2a) and (3a), especially in the western parts of the study area, where high $f_0$ values are observed for scenario (3a). On the other hand in scenario (2a), $f_0$ values are in the range of 1.5–2 Hz for the same area, resulting in a significantly different site-response pattern, controlled by the thicker soil formations.

To further check the previous observations, synthetic $f_0$ values for scenario (1a) were compared with empirical $f_0$ values estimated from $H/V$ spectral ratios from ambient noise measurements (Panou et al. 2005b). Results shown in Fig. 11(a) were produced for a denser grid of receivers employed in the broader area of the historical centre of the city (white parallelogram in Fig. 3). It should be noted that comparisons are presented for scenario (1a), mainly because this is the most typical earthquake scenario for the study area (Fig. 1), since it corresponds to the dominant E–W trending
Figure 8. Variation of the (S2D)/(S1D) ratios along the AA (LEP-OBS), A3 (AGK-KAL) and A5 (AMP-LAB) cross-sections for radial, transverse and vertical components (after Triantafylidis et al. 2004a).
normal faults (e.g. Vamvakaris et al. 2006) from the high seismicity Mygdonia basin area (e.g. Papazachos et al. 1983), almost identical to the earthquake location and fault plane solution employed in scenario (1a). Therefore, Fig. 11(a) has a practical usefulness for future comparisons with instrumental data. In addition, for scenario (1a), the fundamental frequency is clearly identified, as is evident from Fig. 5(a), while for other scenarios (e.g. 1b, Fig. 5b) the fundamental and first higher resonant frequency often 'merge' in a broad spectral amplification peak, resulting in higher apparent \( f_0 \) values (as is also evident from Fig. 10(b) for the same scenario, in comparison to Fig. 10a for the selected scenario 1a). Therefore, the corresponding \( f_0 \) values are not directly comparable with the \( T_{H/V} \) values that are supposed to reflect the local fundamental resonant peak, hence such a comparison would be practically meaningless. The comparison of the \( f_0 \) results shown for scenario (1a) in Figs 10 and 11(a) is generally in a good agreement. The smaller variability of the results of Fig. 10, compared to the ones of Fig. 11(a), is due to the sparser distribution of receivers used in the coarser grid configuration, which cannot identify certain very local effects.

In Fig. 11(b), a comparison of the average fundamental period estimated by the SSR method from 3-D synthetics \( (T_{SSR}) \) with the corresponding average \( H/V \) results from Panou et al. (2005b) \( (T_{SSR}^{Noise}) \) is presented with black circles. Average fundamental periods rather than fundamental frequencies have been used, since they are (very roughly) proportional to the total sedimentary thickness above bedrock. The vertical error bars correspond to ±1 standard deviation (\( \sigma \)) values. For shorter periods (thinner soil formations) a rather good agreement of the estimated average \( T_0 \) values from the two methods is observed, though with rather large standard deviations. However, for longer periods (thicker soil formations) the average \( H/V \) results, \( T_{H/V}^{Noise} \), tend to overestimate (by roughly 30–35 per cent) the average fundamental periods from 3-D synthetics, \( T_{SSR} \). To explore the possible source of this discrepancy, the empirical SSR estimates \( (T_{SSR}) \) from real earthquake recordings (Lachet et al. 1996) for five sites available for the study area are also presented in Fig. 11(b) (white crosses) against the corresponding \( T_{H/V}^{Noise} \) values for the same sites. Despite the lack of data for the period range of 0.7–1 s, the overall trend of the empirical \( T_0^{SSR} \) values against \( T_{H/V}^{Noise} \) is in good agreement with the results derived by the 3-D synthetics and the corresponding \( H/V \) noise ratios. It should be stressed that the three available stations (ROT, LAB and OTE) which exhibit empirical \( T_{SSR} \) lower than 0.5 s (\( f_0 \) higher than the theoretical accurate limit of 2 Hz) are in excellent agreement with the modelled data (solid circles) when compared with observed \( T_{H/V} \) noise measurements, which is further evidence that the simulated data can be reliably used at frequencies higher (up to \( \sim 5 \) Hz) than the 'strict' limit imposed by theoretical estimates.

A roughly similar behavior has been also observed by Rodríguez & Midorikawa (2002) for the city of Yokohama. Their results (also presented in Fig. 11b with open circles) show that the average \( H/V \) results from ambient noise measurements tend to overestimate the fundamental period for a large number of sites, in comparison to the average SSR results using ground motion recordings. It should be noted that data from pattern-1 soil formation (sites close to or in the border of river channels on deluvial and alluvial sediments, according to the categorization adopted by Rodríguez & Midorikawa 2002), have not been included in the comparisons of Fig. 11(b), since they exhibit even larger, unrealistically higher \( T_{H/V}^{Noise} \) values, in comparison to \( T_{SSR} \) results. This apparent bias between the \( T_{H/V}^{Noise} \) and \( T_{SSR} \) values by \( \sim 30–35 \) per cent for thick soil formations, identified in this study results, is marginally higher than the ±25 per cent agreement limit proposed in the study of Haghshenas et al. (2008). Moreover, Rodríguez & Midorikawa (2002) found a good agreement between \( T_0^{Noise} \) and \( T_0^{SSR} \) estimates for several sites, though in almost no case did the \( T_{H/V}^{Noise} \) exhibit lower values than the corresponding \( T_{SSR} \) estimates.

On the other hand, the discrepancy between \( T_{H/V}^{Noise} \) and \( T_{SSR} \) estimates for the city of Thessaloniki could be considered as a real feature, which can be attributed to several reasons. One possible explanation is that this bias has a 'physical' reason, that is, it reflects real characteristics of the wave propagation for thick soil formations of the city of Thessaloniki. For example, it could imply a possible 2-D/3-D effect for the examined sites, since 2-D/3-D sites are characterized by broader transfer functions, due to additional lateral interferences (Cornou & Bard 2003; Cornou et al. 2006). Such broad transfer functions, also observed for some of the empirical SSR curves of Lachet et al. (1996), can 'shift' the \( T_{SSR} \) selection to slightly higher natural periods. A possible 'technical' alternative is that the employed geophysical model for the simulations is less reliable for thick-soil sites, for example, underestimates the bedrock depth, resulting in smaller \( T_{SSR} \) values. However, the good agreement of the average \( T_0^{SSR} \) (empirical) and \( T_{SSR} \) (simulated) estimates in comparison with the average \( T_{H/V}^{Noise} \) values observed in Fig. 11(b), as well as the empirical-synthetic SSR curves comparisons shown in Skarlatoudis et al. (2010) tend to suggest a rather 'physical' reason behind this pattern. This observation suggests that additional modelling of the noise wavefield propagation, as well as new, denser empirical results from earthquake recordings and detailed investigation of the complete transfer functions is required in order to clarify the source of this discrepancy.

5 TIME DOMAIN COMPARISONS

Computations in the frequency domain only provide a partial view of the site-effect impact on ground motions, as several other waveform characteristics (e.g. duration) are only observed in the time domain.
For this reason, synthetic waveforms were also examined for a large number of receivers along the cross-sections shown in Fig. 4, for all six scenarios studied. Note that these results are not normalized over the corresponding bedrock model, as the results shown in Figs 5–7. In most of the scenarios studied wave propagation is dominated by body waves, although in several cases the time–frequency analysis of synthetic waveforms revealed the generation and propagation of surface waves (Love waves), mainly for the deepest sediment parts of the cross-sections.

Results are presented in Fig. 12 for the AGK-KAL cross-section and for the horizontal components of ground motion, which exhibited the most interesting wave propagation features. In the results a clear geometrical spreading impact on the amplitude of the synthetics is observed, especially for scenarios (1a) and (1b) for which the source–receiver distance strongly varies along the cross-section. Anelastic attenuation plays also a more important role for this cross-section, since the sedimentary cover has its larger thickness, in comparison to the other two cross-sections studied. The major difference, though, is the generation and propagation of surface waves, which are identified close to sites LEP and AGK in all six scenarios but mostly for scenarios (2). Seismic source location (almost perpendicular to the cross section) and its distance (closest, in comparison to the other two scenarios) suggest the generation of higher amplitude surface waves for these specific scenarios. The time–frequency analysis of the horizontal components of synthetic waveforms (Fig. 13) revealed the generation and propagation of surface waves with significant amplitudes for scenarios (2) in the U component (north–south). Surface waves start to develop around...
estimates from ambient noise measurements, T
Figure 11. (a) Spatial variation of the fundamental frequency, f_0, estimated for the denser grid of receivers (see Fig. 3), for seismic scenario (1a), using the SSR method on synthetic seismic waveforms. (b) Variation of the average fundamental period estimated using the SSR method on synthetic seismic waveforms of this study, T_{1-D}, against average H/V spectral ratio estimates from ambient noise measurements, T_{\text{Noise}}^{\text{H/V}}, presented by Panou et al. (2005b) for the same sites. The vertical error bars correspond to ±1 standard deviation (σ) values. Empirical SSR results from earthquake recordings (Lachet et al. 1996) against T_{\text{Noise}}^{\text{H/V}} estimates are presented for comparison (white crosses). Similar results from Rodrigues & Midorikawa (2002) for the city of Yokohama are also shown (open circles). The minimum period (0.5 s) for which simulations are theoretically expected to be accurate is denoted with the horizontal dashed line, while the shaded area corresponds to the additional period range (0.2–0.5 s) for which simulations for the city of Thessaloniki have been shown to be practically accurate and reliable (Skarlatoudis et al. 2010).

9.5 s with a frequency around 1 Hz gradually shifting to 3 Hz around 12.5 s, exhibiting prominent dispersion phenomena. Since the source-receiver R1 path for scenario (2) is almost perpendicular to the cross-section AGK-KAL (see Fig. 4a), the N–S component corresponds to the transverse component of seismic motion, hence the surface waves identified are Love waves. Similar conclusions can be drawn for the N–S component of scenarios (1) and possibly for the E–W component of scenario (3a), but characteristics of the generated Love waves are not as prominent as for scenarios (2). Simulations of scenario (1a) for a higher maximum theoretically accurate frequency, F_{ac} = 3 Hz, showed practically identical synthetic waveforms (presented in Fig. S1d), suggesting that the identified Love wave dispersion phenomena do not correspond to numerical dispersion artefacts.

For the LEP-OBS cross-section (scenarios 1 and 2) large amplitudes of body waves are observed, especially for scenarios (2), in the deeper sedimentary cover parts of the cross-section. However, for scenarios (3), the generation and propagation of coda waves with noticeable amplitudes can be also observed in the same part of the cross-section. The previous observations were verified by the time–frequency analysis of horizontal components of ground motion. The analysis showed that body waves are the dominating type of waves propagating along these cross-sections in all scenarios studied, since no dispersion phenomena (typical for surface waves in time–frequency analysis) are found. The generation and propagation of Love waves, suggested by Raptakis et al. (2004b), in the vicinity of the lateral discontinuity between sediments and bedrock was not identified in present study results (especially for scenario 3a, where the source location and focal mechanism are very similar with the simulated earthquake by Raptakis et al. 2004b). The results of the AMP-LAB cross-section study showed that for all six scenarios the largest amplitudes of seismic waves were identified at the area of site LAB, while relatively smaller amplitudes were shown around site AMP. Time–frequency analysis of the horizontal components confirms the domination body waves for all scenarios, with late wave trains observed in scenarios (3) time-series probably corresponding to reflected and not surface waves. The corresponding figures of the previous analysis for LEP-OBS and AMP-LAB cross-sections are available in Supplement S2.

Additional measures that can provide a more detailed evaluation of site effects, such as spectral ratios, PGV, cumulative kinetic energy (Olsen et al. 1995) and Housner intensity (Housner 1952), were also used to probe the site effects spatial distribution and ground motion variability. The FAS ratio for the 3-D over the corresponding 1-D bedrock reference model [(FAS3D)/(FAS1D)] was estimated for the coarser grid of receivers and for the two horizontal components of ground motion, for all scenarios studied. The spatial variability of [(FAS3D)/(FAS1D)] ratio was computed for four different frequencies 0.5 Hz (2 s), 1 Hz (1 s), 2 Hz (0.5 s) and 4 Hz (0.25 s) and the average ratio from the six scenarios for the frequency of 4 Hz (0.25 s) is presented in Fig. 14. The corresponding figures for the remaining frequencies studied are available in Supplement S3. The largest spectral ratio values (7–8) are observed for the N–S component in the SE part of the model, as well as in the E–W component (~6) in the broader area of the historical centre of the city. The lower figures in Fig. 14 present the corresponding standard deviation of the [(FAS3D)/(FAS1D)] ratio. The largest variability is found for the E–W component of ground motion and for the central-SE parts of the model, with values ranging between 2 and 3.4.

The largest values of the spectral ratio are identified for the frequency of 2 Hz (~15) in the central-SW and western parts of the
Figure 12. (a) Horizontal component $U$ (north–south) calculated at free surface for the six scenarios, for cross-section AGK- KAL. (b) Horizontal component $V$ (east–west) calculated at free surface for the six scenarios, for cross-section AGK- KAL.
Figure 12. (Continued)
Figure 13. (a) Time variation of the power spectrum for the horizontal components of synthetic waveforms for receiver R1 (open triangle in Fig. 4) of the AGK-KAL cross-section and scenarios (a). (b) Time variation of the power spectrum for the horizontal components of synthetic waveforms for receiver R1 (open triangle in Fig. 4) of the AGK-KAL cross-section and scenarios (b).
Distribution of site effects in Thessaloniki

Figure 13. (Continued.)

© 2011 The Authors, GJI, 185, 485–513
Geophysical Journal International © 2011 RAS
model and for the N–S and E–W components of ground motion, respectively. The corresponding standard deviation values are also relatively high for both horizontal components, denoting the large variability of the estimated values of \([\text{FAS3D}/\text{FAS1D}]\) ratio between the studied scenarios for this specific frequency (4 Hz). On the other hand, the values of \([\text{FAS3D}/\text{FAS1D}]\) ratio are considerably smaller when studying lower frequencies (0.5 and 1 Hz), showing higher values only for those parts of the model where the thick sedimentary formations are dominant.

A similar procedure was adopted for the study of the spatial distribution of the PGV values. In Fig. 15 the spatial distribution of average relative PGV [PGV3D/PGV1D], for the six scenarios studied (top figures), as well as the corresponding distribution for scenario (1a; lower figures) are presented for the horizontal components of ground motion. As earlier described, scenario (1a) was selected as it corresponds to the most typical earthquake scenario for the city of Thessaloniki, since most of the large events from E–W normal faults occur in the high seismicity Servomacedonian massif (Fig. 1) located to the NW of the study area. The observed relative PGV distribution from the six scenarios, exhibits high values along the coastal zone, with the highest value (∼4) shown in the area near the city harbour for the E–W component. High values of relative PGV are also observed in the western parts of the model for the E–W component, both for the average values from the six scenarios, as well as for scenario (1a). The highest values (∼6) for scenario (1a) and for the N–S component are observed in the

---

**Figure 14.** Top panel: spatial variation of the average values, from the six seismic scenarios, of the ratio \([\text{FAS3D}/\text{FAS1D}]\) for the horizontal components of ground motion, estimated for the coarser grid of receivers (see Fig. 3) and for the frequency of 4 Hz. Bottom panel: spatial variation of the standard deviation values of the ratio \([\text{FAS3D}/\text{FAS1D}]\).
Distribution of site effects in Thessaloniki

Figure 15. Top panel: spatial variation of the average, from the six seismic scenarios, ratio [(PGV3D/PGV1D)], for the horizontal components of ground motion, estimated for the coarser grid of receivers (see Fig. 3). Bottom panel: spatial variation of the ratio [(PGV3D/PGV1D)], for the horizontal components of ground motion, estimated for the coarser grid of receivers (see Fig. 3) and for seismic scenario (1a).

northern part of the model. The strong spatial variability observed in the results for scenario (1a) in comparison to the average scenario indicates that the PGV distribution does not reflect only the effect of local structure but strongly depends on the specific source position and type.

Both the PGV and spectral ratio values do not adequately reflect some characteristics of the seismic motion, such as the signal duration or its total energy content. For this reason, the cumulative kinetic energy per unit volume (Olsen et al. 1995), $E_k$, was also employed in the comparisons, as it is given by

$$E_k (x, y, z) = \frac{1}{2} \rho (x, y, z) \int \dot{u}_k^2 (x, y, z, t) \, dt,$$

where $\rho (x, y, z)$ is the density, $\dot{u}_k$ is the $k$th component of ground velocity and the integration is performed over the time duration of the simulation. Since $E_k$ corresponds to the total kinetic energy, it was estimated from both horizontal components of synthetic waveforms for the six scenarios studied, therefore representing a more ‘average’ strong motion measure of each site. In order to minimize geometrical spreading and source effects, $E_k$ was similarly estimated for both the AN01 geophysical model ($E_{k3D}$) and the corresponding bedrock 1-D model ($E_{k1D}$).

The spatial distribution of the average ratio from the six scenarios studied [(PGV3D/PGV1D)] and for scenario (1a) are presented in Fig. 16. The highest values are located essentially in the same areas (historical centre of Thessaloniki, coastal zone in the SE part of the model and small areas in the northern part of the model) where thicker recent soft-soil sedimentary formations are found (see Fig. 4a). These high-amplification areas where also identified in the frequency analysis along the three cross-sections (Figs 5–7), as well as the FAS spatial distribution results. Moreover, this observation is in accordance with Fig. 12, where the duration of waveforms in the coastal areas (thicker sedimentary cover) is significantly longer compared to bedrock sites producing, thus, higher values of cumulative energy. Results for scenario (1a; bottom maps, Fig. 16) do not differ significantly from the ones presented for the average values.
for all scenarios. This observation shows that the cumulative kinetic energy (which combines both horizontal components) provides results that are mostly controlled by the local structure and are less sensitive to the changes of the wavefield excitation sources.

The Housner or response-spectrum intensity (SI) has been originally proposed (Housner 1952) as a measure of the damage potential of an earthquake and is given by relation

$$\text{SI}(\xi) = \int_{T_1}^{T_2} PSV(T, \xi) dT,$$

(6)

where $PSV$ is the velocity spectrum defined as the maximum response in terms of velocity of an elastic single degree of freedom system submitted to the ground motion under consideration. The integral of eq. (6) is usually computed for $T_1 = 0.1$ s (10 Hz) and $T_2 = 2.5$ s (0.4 Hz), recognizing that most structures have a fundamental period in this period range. Since, the source–time function used in the simulations (eq. 4) has sufficient energy up to the frequency of 3 Hz (0.33 s), Housner intensity was computed for a modified period range [$T_1 = 0.33$ s, $T_2 = 2.5$ s]. Similar to previous estimates, we examined the spatial distribution of the ratio [(SI3D/SI1D)], estimated for the 3-D over the corresponding 1-D bedrock reference model. In Fig. 17(a) the spatial variation of the average ratio from the six scenarios studied [(SI3D/SI1D)] together with the standard deviation values are presented, while in Fig. 17(b) the spatial variation of the ratio for scenario (1a) is also given, in order to allow the evaluation of the variability of predicted site effects between the different scenarios. Similarly with the previous measures studied, the highest values of the ratio are identified for
the same model areas, as with other measures, though with higher variability than the kinetic energy, as high standard deviation values are found for the central SE (∼1.3) part of the model, mainly for the E–W component. Comparison with the results presented in Fig. 17(b) (scenario 1a), shows a relatively small spatial variability, however, SI ratio values for this scenario are relatively higher for the central parts of the model and for the N–S component, indicating a source dependent distribution, similar to spectral ratios and PGV.

6 DISCUSSION AND CONCLUSIONS
The spatial variation of site response for metropolitan area of Thessaloniki has been studied in detail using a 3-D FD scheme. We extend the results of Skarlatoudis et al. (2010) by studying the FAS ratios estimated for a 3-D model (FAS3D) computed for six different source scenarios. The geometry and properties of the soil formations of the modified geophysical–geotechnical model of Anastasiadis et al. (2001) were used in order to construct the computational model used in the FD simulations. The corresponding 1-D bedrock reference model was also used for computing 1-D Fourier amplitude spectra ratios (FAS1D) and other seismic motion measures (PGV, SI, $E_k$), in order to partly remove path and source effects from our results.

The frequency variation of the (FAS3D/FAS1D) ratios reveals the combined impact of the seismic source—3-D model on the local site-response. More specifically, a strong dependence of the (FAS3D/FAS1D) ratio on the source properties was also observed, even for results from scenarios with the same source location and different focal mechanisms. Results along the typical LEP-OBS...
cross-section which spans the central part of the city and runs almost normal to the local geology trend from the bedrock to the thick sediments of the coast, showed the existence of two distinct high-amplification zones in the frequency domain for both horizontal components and for the majority of the scenarios studied. The first zone is controlled by the bedrock–sediments discontinuity, exhibiting relatively lower amplification amplitudes. The second band is locally characterized by often higher amplification amplitudes, corresponding to the contrast of the shallow soft-soil sediments (A, C, B) to the E/F formation discontinuity. The fact that the two zones are not clearly formed (or even present) in all examined scenarios, as well as the partial frequency shifting of these bands for the various scenarios examined verifies the impact of the 3-D model geometry and the corresponding complex 3-D wave propagation features on the local characteristics of site-response.

For the AGK-KAL cross-section the north–south components exhibit high amplitudes around the frequency of 2 Hz, extending from site KAL up to the distance of 4000 m along the cross-section. A second zone, with relatively lower amplifications, is identified around the frequency of 1 Hz in almost all scenarios and components of ground motion. These two areas of higher amplification probably correspond to trapped waves in the surficial layers of the model (higher frequency band), while the latter (lower frequency band) to the bedrock sediments discontinuity. Moreover, significant amplifications are also found in the vertical component in scenarios (1) around the frequency of 1 Hz. This is the only case for all examined scenarios and cross-sections where such high amplifications are found for the vertical component. Finally, the third cross-section studied (LEP-LAB) exhibits the highest amplifications, with two amplification ‘lobes’ identified around the sites AMP and LAB where the thicker sedimentary formations of the model are found. Large differences are observed for the amplifications between scenarios (1) and (3), with the most prominent feature being the alternation of the highest amplifications between sites AMP and LAB in scenarios (3a) and (3b).

It should be noted that the 3-D modelling employed in this study is important not only due to the complex 3-D geometry of the sediments-bedrock contact but also due to the strong variations of the more surficial formations, as observed in Fig. 4. This becomes clearer by the study of the shallower sediment formations, which appear to locally exhibit a more or less 1-D structure, leading to expectation of a 1-D response, possibly enhanced by the presence of surface waves generated at the edges of the model. However, this is not the case in almost all examined cross-sections, with much more complicated changes being present for the higher resonant frequency bands. A typical example can be observed for the area around site KAL (AGK-KAL cross-section), as this is presented in Fig. 6. For this area scenario (1a) shows that the next higher resonant frequency after the fundamental (which is around 0.5 Hz), is located at ∼1.7 Hz. This estimation changes to ∼1.6 Hz for scenario (1b) (with a narrow-band amplification peak) and is shifting further to ∼2.1 Hz for scenario (3a) (with a broad-band amplification peak). Such changes indicate that although one might expect a rather 1-D response along this typical cross-section, since formations A and B are apparently almost 1-D, their small-scale 3-D variations (e.g. see Fig. 4b), as well as the strong overall 3-D variability of the deeper formations (e.g. bedrock), in combination with the source position and type, render the expectation of a simple 1-D response plus surface waves not valid along this typical cross-section.

The spatial variation of site response for the metropolitan area of Thessaloniki was also studied by mapping the spatial distribution of the fundamental frequency, $f_0$, using the SSR method on the synthetic waveforms with respect to the OBS reference site. The impact of 3-D effects on site response, suggested by the $f_0$ spatial distribution, is also verified by the examination of the frequency variation (FAS3D/FAS1D) for the various seismic scenarios. The previous results suggest a different concept regarding how site effects should be considered by engineering seismologists and earthquake engineers, since different soil responses appear to be ‘triggered’ when the earthquake source parameters and/or location are varying, resulting in strong variations of the final site-response.

The comparison of the fundamental period estimated with the SSR method from 3-D synthetics ($T_{(3-D)}$) with the corresponding $H/V$ results from Panou et al. (2005b) ($T_{(H/V)}$) shows a good agreement for shorter periods (relatively thin soil formations), while for longer periods (thicker soil formations) the $H/V$ results ($T_{(H/V)}$) tend to
ground motion recordings, especially for thicker soil formations of a specific site, compared to the SSR method from earthquake measurements also appears to overestimate the fundamental period.

Synthetic waveforms are also compared in the time domain along the three selected cross-sections. Significant differences between amplitudes and duration of synthetics among the various scenarios are noticed. These differences are more evident for the AGKKAL cross-section, where the generation and propagation of surface waves is observed for scenarios (2) and partly (1). Time–frequency analysis as well as the source–receiver geometry for this cross-section, suggest that the generated surface waves correspond to locally generated Love waves. The previous results verify the complexity of 3-D site response along the three examined cross-sections studied, suggesting that it is not possible to define a unique site response of the various sites to different seismic excitations, as these are affected not only by the change of seismic source location but also by the different seismic source properties (e.g. different focal mechanism).

Most of the seismic motion measures employed for studying the ground motion variability and site-effect spatial distribution, [PGV, FAS3D/FAS1D, cumulative kinetic energy (Eg) and Housner intensity (SI)] show that the amplification pattern is controlled by the combination of two major factors: (i) The geometry of the bedrock–sediments contact and (ii) the thickness of the recent soft-soil sediments (see Fig. 4a). As a result, ground motions generally increase with the total sedimentary thickness, while the highest expected ground motions are found in the southern-central part of the model and especially along the coastal zone. Despite this common pattern of the various ground motion measures studied, important differences are also identified, which are controlled by the intrinsic properties of each measure (e.g. PGV which is based on the peak value of time-series and SI which is computed from the velocity spectrum for a specific period range) and as an extension on the frequency band for which each measure is sensitive. A typical example is the case of Spectral Amplification ratios [FAS3D/FAS1D], where the spatial distribution at low frequencies (0.5 and 1 Hz, see Figs S3a and b) is clearly controlled by the total sedimentary thickness structure, exhibiting the highest values in areas (e.g. southern coastal zone) where the thickest recent soft-soil sedimentary formations (soil formations A, B and C) are observed (Fig. 4a). On the contrary, the corresponding ratios estimated for higher frequencies (e.g. 4 Hz, see Fig. 14) exhibit their highest values for areas where the same recent sediment formations have intermediate depths (~10–30 m), with lower amplitudes observed in the area of thickest sediments (southern coastal area).

ACKNOWLEDGMENTS

We would like to thank Dr. J. Kristek, Prof. P. Moczo, Prof. J. Virieux and the two anonymous reviewers for their comments and suggestions which helped to improve the present work. This work has been partly supported by project PENED-2003 (measure 8.3, action 8.3.4 of the 3rd Community Support Programme) and the Greek–Slovak Cooperation Agreement (EPAN 2004–2006).

REFERENCES


Schermbaum, F., Ohrnberger, M., Savvidas, A., Panou, A.A. & Theodoulidis, N., 2002. Determination of shallow shear wave velocity profiles using ambient vibrations at selected sites in Greece, Poster at the Assembly of the American Geophysical Union.


SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Supplement S1. Evaluation of present study results with respect to various aspects of the computational model.

Figure S1a. Comparison of 3-D (blue curves) and 1-D (red curves) synthetics, for the reference site OBS and for scenarios (1a) and (1b).

Figure S1b. Comparison of waveforms for computations theoretically accurate up to the frequency of 2 Hz (black curves) and 3 Hz (red curves), for sites residing on formation B and for scenario (1a).

Figure S1c. Synthetic SSR curves for receivers residing on sites where formation B has significant thickness, for scenario (1a). SSR curves produced by synthetics theoretically accurate up to $F_w = 2$ Hz are shown with the black curves, while for $F_w = 3$ Hz are shown with the red curves, respectively.

Figure S1d. Comparison of the NS component of receiver R1, of synthetics theoretically accurate up to $F_w = 2$ Hz (black curves) and theoretically accurate up to $F_w = 3$ Hz (red curves) for scenario (1a), bandpass filtered in 0.2–5 Hz.

Supplement S2. Time-domain analysis along the selected cross-sections for the six scenarios studied.

Figures S2a, S2b. Horizontal components, U (north–south) and V (east–west), calculated at free surface for the six scenarios, for cross-section LEP-OBS.

Figures S2c, S2d. Horizontal components, U (north–south) and V (east–west), calculated at free surface for the six scenarios, for cross-section AMP-LAB.

Supplement S3.

Figure S3a. Spatial variation of the average values, from the six seismic scenarios, of the ratio [(FAS3D/FAS1D)] for the horizontal components of ground motion, estimated for the coarser grid of receivers (see Fig. 3) and for the frequency of 0.5 Hz. (Bottom) Spatial variation of the standard deviation values of the ratio [(FAS3D/FAS1D)].

Figure S3b. Spatial variation of the average values, from the six seismic scenarios, of the ratio [(FAS3D/FAS1D)] for the horizontal components of ground motion, estimated for the coarser grid.
of receivers (see Fig. 3) and for the frequency of 1 Hz. (Bottom) Spatial variation of the standard deviation values of the ratio $[(FAS3D/FAS1D)]$.

**Figure S3c.** Spatial variation of the average values, from the six seismic scenarios, of the ratio $[(FAS3D/FAS1D)]$ for the horizontal components of ground motion, estimated for the coarser grid of receivers (see Fig. 3) and for the frequency of 2 Hz. (Bottom) Spatial variation of the standard deviation values of the ratio $[(FAS3D/FAS1D)]$.

Please note: Wiley-Blackwell are not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.