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Stochastic strong ground motion simulation of intermediate depth earthquakes: the cases of the 30 May 1990 Vrancea (Romania) and of the 22 January 2002 Karpathos island (Greece) earthquakes

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Abstract

Stochastic finite-fault simulation is used to simulate the acceleration time histories of two intermediate depth ($h \sim 90$ km) earthquakes, which occurred on 30 May 1990 in Vrancea (Romania) and on 22 January 2002 near Karpathos island in Greece. Site amplification functions were used for all stations included in the simulation process. For the Romanian earthquake, peak acceleration values were observed at the more distant from the epicentre stations. In Romania, strong anisotropy in Q -values was observed along the NE–SW direction (along strike of the fault) compared to the normal to the strike of the fault direction. Specific site corrections were required for the station in Bucharest, employing the H/V ratio technique, to refine the site-specific amplification function and achieve better match of the simulated spectra. In the Aegean Sea region, average values for attenuation and site amplification functions were used for all stations with overall satisfactory results. Any unmatched discrepancies between observed and simulated spectra would require further accurate knowledge of the site characteristics. © 2003 Elsevier Ltd. All rights reserved.

Keywords: Ground motion simulation; Vrancea; Aegean sea; Earthquakes

1. Introduction

The Vrancea region in Romania and the Hellenic Arc in Greece are well-known subduction zones, where intermediate focus ($60 \text{ km} < h < 300 \text{ km}$) earthquakes occur. These regions have suffered from destructive earthquakes in the past with casualties both in human lives and surface structures. Understanding the source processes of intermediate depth earthquakes and studying their effects on the earth's surface is a very interesting task in further attempts concerning the a priori prediction of future ground motions.

Vrancea is located at the sharp bend of the South Eastern Carpathian mountains (Fig. 1). It signs a complex intra-continental collision process and is now considered to be in a final stage of evolution [1]. The volume of the subducted slab, still seismic active, is very confined (Fig. 1) and seems to be decoupled from the overlying crust. Strong earthquakes occur between 70 and 180 km depth within an almost

vertical column. The depth interval of strong events is bounded by levels of low seismicity between 40 and 60 km and beneath 180 km. According to Musson [2], the highest hazard in the north Balkan region comes from the intermediate depth earthquakes of Vrancea. Within the last 20 years, Bucharest was threatened by three earthquakes with magnitude $M_w > 6.5$.

The Hellenic arc, one of the most prominent tectonic features of the Aegean Sea (Fig. 1), has formed as the result of the convergence between the Aegean and the African plates, and has attracted the attention of many scientists (McKenzie [3]; Taymaz et al. [4,5]; Kiratzi and Papazachos [6], among many others). Subcrustal seismicity in the Aegean Arc reaches depths up to 180 km [6] and their magnitudes, based on historical data, can be as high as $M_w \sim 8.3$ [7]. However, no such earthquake occurred during instrumental times and their repeat times are thought to be of the order of thousands of years [7]. These intermediate focus events usually have strong effects on the outer part of the Hellenic arc and damage in residential areas has been reported in historical records in Italy, Egypt, even in countries of the Middle East [7]. In the Greek territory, the most affected

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Fig. 1. Regional map showing the location of Vrancea region in Romania and the Hellenic Arc in Greece.

areas are the islands of the south Aegean Sea and mostly the highly populated islands of Crete and Rhodes.

Fig. 2A–D presents the seismicity of the two areas studied. Fig. 2A, B depicts the epicentres of shallow and intermediate depth earthquakes, respectively, which occurred at the broader northeastern Balkan peninsula from 1906 to 2002. In total, ~6000 epicentres are plotted as derived from the on-line bulletin of the International Seismological Centre [8]. Shallow ($h < 60$ km) seismicity is of moderate magnitude and diffused compared to the subcrustal seismicity, which concentrates in a confined volume at intermediate depths of 60–300 km. One to five subcrustal shocks with $M_w > 7$ occur in this region every century and are widely felt. Previous subcrustal destructive events reported from the beginning of the 19th century occurred on 26 October 1802 ($M_w = 7.9$), on 26 November 1829 ($M_w = 7.3$), on 11 January 1838 ($M_w = 7.5$) and on 4 March 1977 ($M_w = 7.5$) [9].

Fig. 2C, D depict the epicentres of shallow and of intermediate depth earthquakes, respectively, which occurred in the Aegean Sea and the surrounding lands [10]. It is observed that the intermediate focus earthquakes

have epicentres that are located mostly in the southern Aegean Sea.

In the present study, we study two earthquakes, with focal depths ~90 km, which occurred in Vrancea and in the Hellenic arc. We stochastically simulate the observed ground motions of the 30 May 1990 ($M_w = 6.9$) Vrancea event and of the 22 January 2002 ($M_w = 6.1$) Karpathos island earthquake at the southeastern part of the Hellenic Arc. We took into account the site conditions on the ground motions, and we also perform an extensive parametric study of other parameters, like Q , which also affect the simulation results.

2. Data

For the 30 May 1990 ($M_w = 6.9$) Vrancea earthquake, the data were derived from the European strong-motion database [11]. Seventeen accelerograms were used, obtained from six stations installed on various sites (Table 1). Unfortunately, site classification was available for only two of the six stations. For that reason, we adopted stiff soil site classification for the rest of the sites.

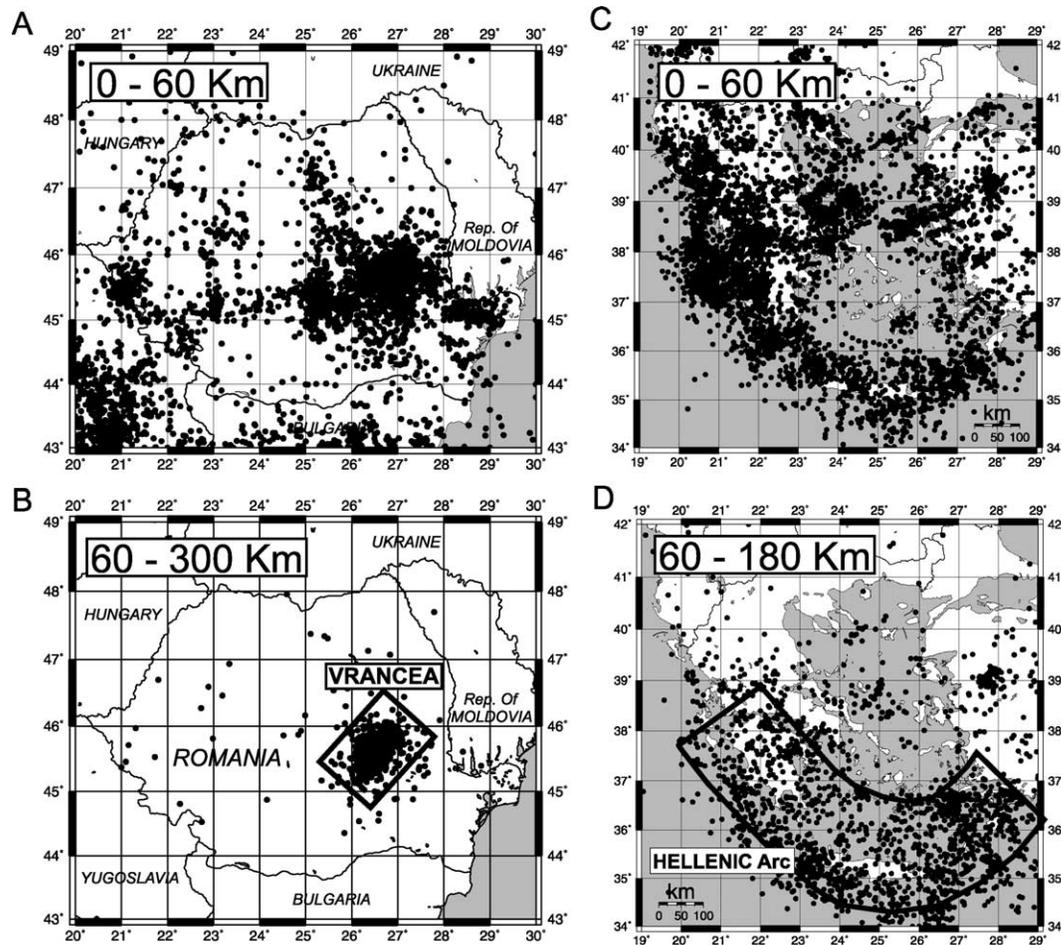


Fig. 2. (A and B) Epicentres from ISC bulletins of ~ 6000 shallow depth ($h < 60$ km) and intermediate depth (60–300 km) earthquakes for the north-eastern Balkan peninsula from 1906 to 2002. (C and D) Epicentres of shallow and intermediate depth earthquakes for the Aegean Sea and the surrounding lands (data from Ref. [10]). Intermediate focus earthquakes have epicentres that are confined in the southern Aegean Sea.

The classification of the sites was done following Boore et al. [12], which is based on the measured or estimated average shear-wave velocity to a depth of 30 m (V_{s30}). For Vrancea earthquake, the two sites for which we have information have been classified as rock ($V_{s30} > 750$ m/s) and alluvium sites ($V_{s30} < 180$ m/s). The recording instruments are analogue accelerographs (Kinometrics SMA-1) installed at distances ranging from 5 to 202 km from the epicentre. The records used here were digitised at 100

samples/s and band-pass filtered (0.1–25 Hz) using an eighth order elliptical filter, as part of a standard process applied to all records of the European strong-motion database [11].

For the 22 January 2002 ($M_w = 6.1$) Karpathos island earthquake, the data were obtained from the permanent broad-band network equipped with Lennartz LE-3D/20 seismometers and operated by the Geodynamic Institute of the National Observatory of Athens. We used broad-band data because none of the accelerographs of the national

Table 1
Information on the strong-motion and broad-band stations used in the present study

Code	Station name	Country	Epicentral distance (km)	Lat. (°)	Lon. (°)	Foundation category
VRI	Vrancioa	Romania	5	45.866	26.727	Rock
–	Istrita	Romania	80	45.138	26.545	Unknown
–	Birlad	Romania	88	46.266	27.626	Unknown
–	Bucharest	Romania	162	44.441	26.161	Alluvium
IAS	Iasi	Romania	165	47.193	27.562	Unknown
CER	Cernavoda	Romania	202	44.314	28.032	Unknown
NPS	Neapolis	Greece	97	35.26	25.61	Rock
ARG	Archangelos	Greece	154	36.22	28.13	Rock
APE	Aperanthos	Greece	189	37.07	25.53	Rock

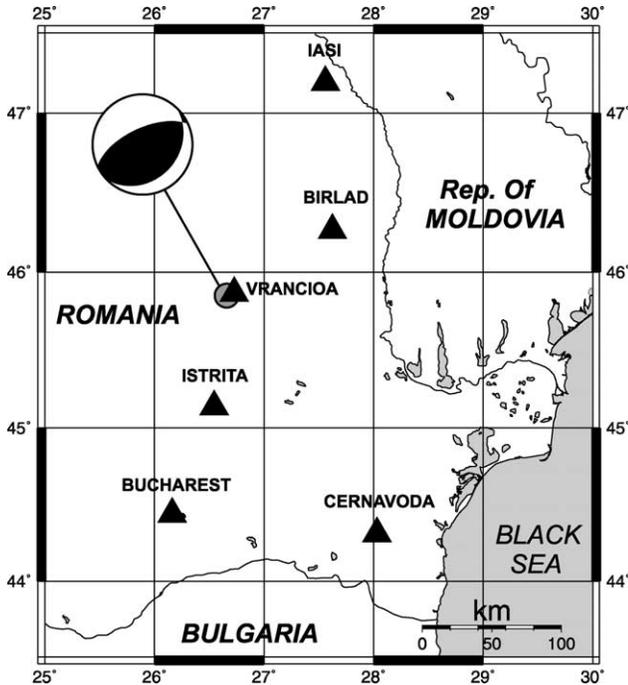


Fig. 3. Focal mechanism of the 30 May 1990 Vrancea earthquake (from Ref. [17]) and location of the strong-motion stations used in the simulation process.

networks of Greece have been triggered by the Karpathos earthquake. The ground motion simulations were done for three stations located on the islands of Crete, Rhodes and Naxos, the most populated islands of the Aegean Sea. As the primary waveforms were velocity records, we obtained the acceleration records through differentiation. Rock site classification was adopted for all three stations.

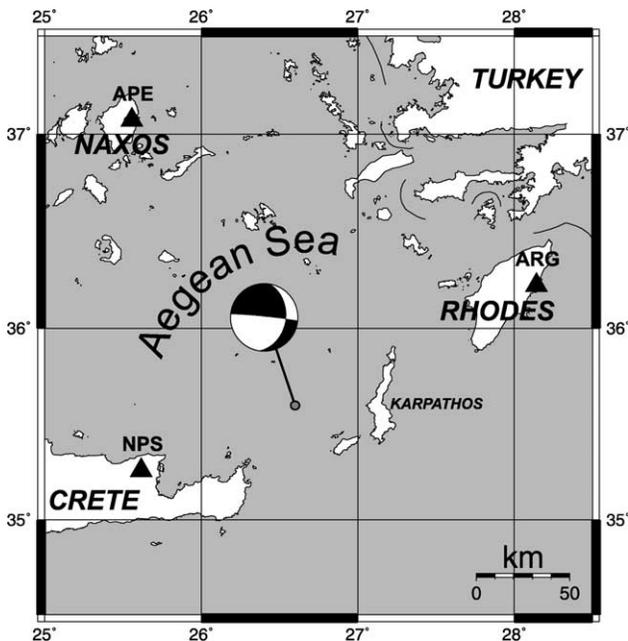


Fig. 4. Focal mechanism of the 22 January 2002 Karpathos earthquake (from Ref. [19]) and location of the broad-band stations used in the simulation process.

Information for all stations is given in Table 1 and their locations are shown in Figs. 3 and 4 along with the focal mechanisms of the two events studied.

3. Method

The method used for the ground motion simulations is the stochastic finite-fault technique of Beresnev and Atkinson [13–15]. In this method, the finite source is represented by a rectangular plane, which is subdivided into a number of elements (subfaults). Each one is treated as a point source and the location of the hypocenter is selected. The rupture begins from the hypocenter and spreads radially from it triggering the adjacent elements when it reaches its centre. The contribution from all the elements are lagged and summed at the receiver. Each subevent has an ω -square spectrum. The ground motion at an observation point is obtained by summing the contribution over several subfaults. Rupture propagation is simulated by a simple kinematic model of the Hartzell [16] type and propagation effects are empirically modelled by using observed regional dependence of amplitude and duration on distance.

Beresnev and Atkinson [13] linked the corner frequency f_c to subfault dimension Δl through the relation

$$f_c = \frac{\left(\frac{yz}{\pi}\right)\beta}{\Delta l}$$

where β is the shear-wave velocity (km/s), y is the ratio of rupture velocity (km/s) to β and z the product of s_{fact} and 1.68. The s_{fact} parameter controls the amplitudes of the radiation at frequencies higher than the corner frequency of the subfaults and has been linked to the maximum velocity of slip on the fault. Acceptable range for the values of s_{fact} is 0.7–2.0. We tested different values between the upper and lower limit of s_{fact} and we finally chose $s_{\text{fact}} = 1.5$ and 1.4 for the Vrancea and the Karpathos events, respectively. The discretization of the fault was done in such a way so as to obtain the best fit between spectral shapes for both earthquakes studied. The material properties are described by density ρ , and shear-wave velocity β and the values adopted for them were 2.7 g/cm³ and 3.9 km/s, respectively, for both earthquakes studied. Due to the large depths of the earthquakes, we adopted average values representative for the whole seismic path from the hypocenter to the receivers. We kept the value of the stress parameter to 50 bars as suggested in Ref. [13].

The focal mechanism estimated by Perrot et al. [17] was used in the ground motion modelling of the Vrancea event (Fig. 3). The estimated source area was 235–285 km² [18]. Taking an average value of 260 km² and based on the spatial distribution of the aftershocks [18], the length of the fault along strike was chosen to be 12 km and along dip 22 km. As reported in Ref. [18], we assumed the NW dipping plane

as the fault plane and we adopted the location of the hypocentre at a depth of 90 km.

For the Karpathos event, the fault plane solution of Benetatos et al. [19] was used for our simulations (Fig. 4). The fault dimensions were calculated from empirical relations applicable to Greece [20]. We adopted a 18×11 km fault, and based on our waveform modelling results [19], we located the hypocenter at 91 km. We assumed the WNW–ESE trending plane as the fault plane based on the work of Papazachos and Panagioto-poulos [21] and of Tibi et al. [22,23].

The attenuation model used for the Vrancea earthquake is of the form $Q(f) = 380f^{0.39}$ and is an average value valid for a subduction zone that was adopted for the Romanian territory [24]. For the Karpathos event, we used $Q(f) = 150f^{0.8}$ (average value from Refs. [25, 26]). Both Q -values were derived from both S- and coda wave analysis. For the geometric attenuation, we applied a geometric spreading operator of R^{-1} for distances $R \leq 100$ km and $R^{-1/2}$ for distances $R > 100$ km [27].

The effects of the near-surface attenuation were also taken into account by diminishing the simulated spectra by the factor $\exp(-\pi k f)$ [28]. The kappa operator (κ) was given the values 0.035s for rock sites, 0.05s for stiff soil sites and 0.066s for alluvium sites [29,30]. Site amplification was also taken into account by employing site amplification functions derived from the work of Oncescu et al. [31] for the Vrancea earthquakes and by average amplification functions of Boore and Joyner [32] for the Aegean Sea event. No information was available regarding the slip distribution on the fault surfaces, so we adopted a random normally distributed slip for both cases. The hypocenters were located at the centre of the lower part of the faults suggesting upward bilateral rupture for both events. Table 2 lists the modelling parameters used in the simulations.

Table 2
Modeling parameters used for the simulation method

Parameter	VRANCEA EQ	KARPATOS EQ
Fault orientation	Strike 245°, dip 63°	Strike 278°, dip 88°
Depth of upper edge of fault (km)	75	84
Fault dimensions (km)	12 × 22	18 × 11
Moment magnitude (M)	6.9	6.1
Stress parameter (bars)	50	50
Subfault dimensions (km)	4.0 × 4.4	2.6 × 2.8
Subfault corner frequency (Hz)	0.60	0.88
Crustal shear wave velocity (km/s)	3.9	3.9
Crustal density (g/cm^3)	2.7	2.7
$Q(f)$	$380f^{0.39}$	$150f^{0.8}$
Distance-dependent duration term (s)	1.4 ($R \leq 50$ km); $+0.07 \times R$ ($R > 50$ km)	
Geometric spreading	R^{-1} ($R < 100$ km) $R^{-1/2}$ ($R > 100$ km)	
Windowing function	Saragoni-Hart	
Kappa operator (κ)	0.035 (rock), 0.05 (stiff soil), 0.066 (alluvium)	

4. Results

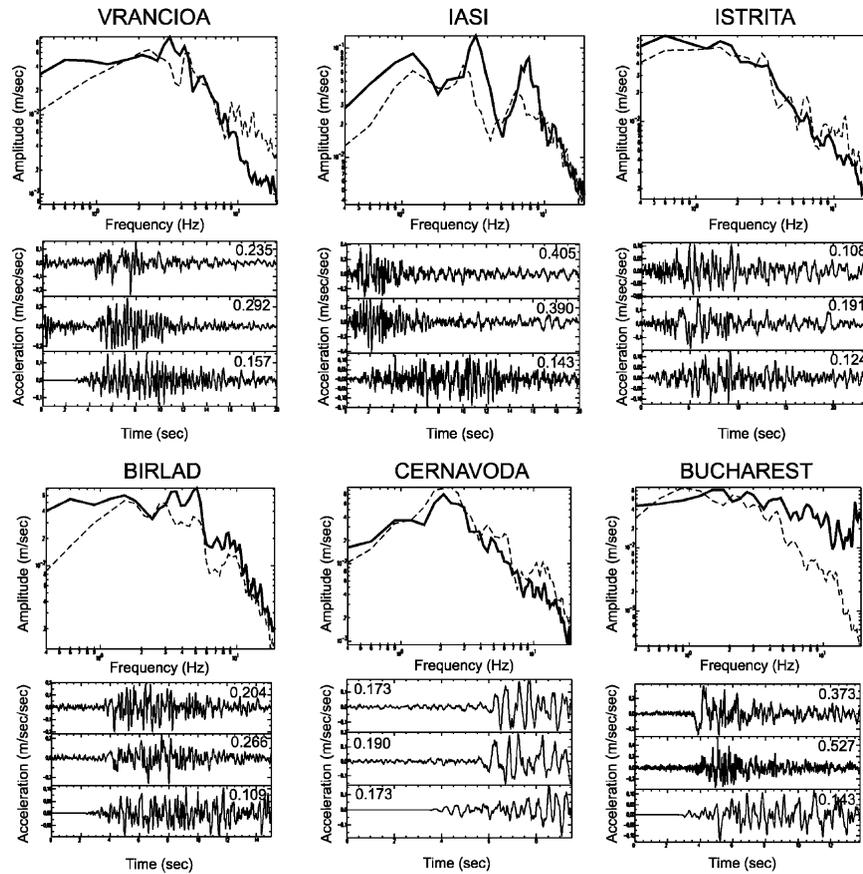
Fig. 5 compares the Fourier spectra—amplified by the applied amplification functions—as well as the recorded and simulated accelerograms at the station sites. For the case of Vrancea earthquake, the site-specific amplification functions were derived from S-wave analysis using a source–site separation method (Joint Source–Site Determination method) [33]. For Karpathos earthquake simulations, the mean amplification function used was derived from velocity estimations using borehole data. The velocities as a function of depth were then used to compute frequency-dependent amplifications for zero attenuation to be used in strong ground motion simulations [32]. The observed spectrum (continuous trace) at each site is the average of the spectra of the two horizontal components. Below the spectra, we present the S-wave part of both the north–south and east–west acceleration components (top two traces, respectively). The simulated trace (bottom trace) corresponds to a random horizontal component and has a sampling interval equal to that of the original recorded traces.

4.1. 30 May, 1990 Vrancea earthquake (M_w 6.9)

For the Vrancea earthquake, the shape and amplitudes of the observed spectra are well matched at almost all stations in the frequency range (1–10 Hz). A significant discrepancy at high frequencies (5–10 Hz) exists at Bucharest and Iasi stations, where the peak ground acceleration values are underestimated by almost a factor of 3. These are the most distant stations from the epicentre in the NE–SW direction. We searched the parameters, which could affect our simulations and anisotropy in the attenuation seemed the most probable factor.

We noticed that less attenuation for the stations situated along strike (NE–SW direction) compared to the normal to

Vrancea earthquake 30 May, 1990



Karpathos Isl. Earthquake 22 January, 2002

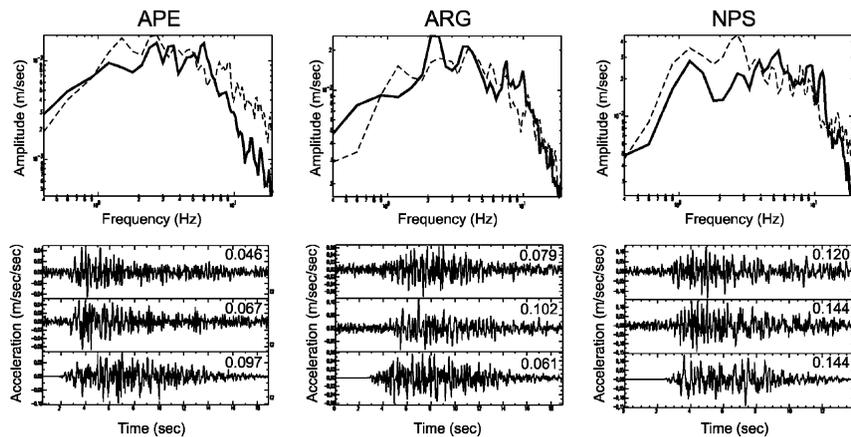


Fig. 5. Fourier spectra and acceleration time histories for the 30 May 1990 Vrancea earthquake and the 22 January 2002 Karpathos island earthquake, at the stations shown in Figs. 3 and 4, respectively. Top figures: observed Fourier spectra (continuous lines) and simulated Fourier spectra (dashed lines). Bottom figures: the upper two traces are the recorded horizontal components and the lower trace is the simulated random horizontal component. The peak value for acceleration is shown for each trace.

the strike stations, resulted in better match between the observed and the simulated records. This anisotropy of attenuation has been also observed by Lungu et al. [34,35], Musson [2] and Radulian et al. [36]. Thus, for the Bucharest and Iasi stations, we employed larger Q -values more representative of the depth of the event and the path from the source to the stations. Furthermore, to improve the shape

matching of the spectra at Bucharest station, we used the H/V ratio technique, applied to the mainshock recordings, to produce a site-specific amplification function, and the results are shown in Fig. 6. This technique is frequently used for site effect estimation and consists in taking the spectral ratio between the horizontal and the vertical component of the shear-wave part. We could not apply

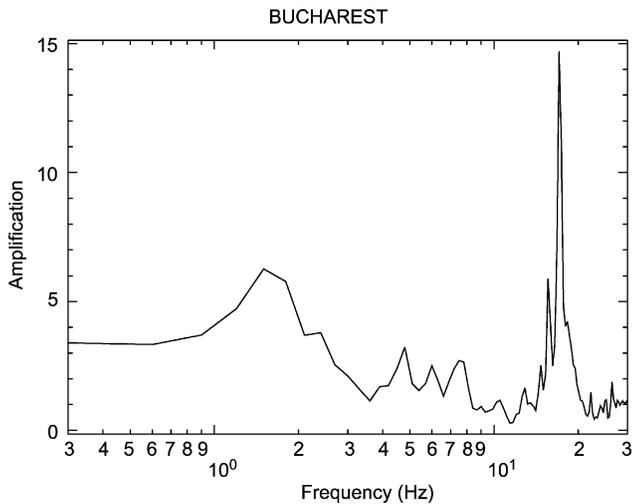


Fig. 6. Site amplification function for the Bucharest station estimated by the H/V ratio technique using the mainshock recordings.

the H/V procedure for Iasi station simply due to lack of records from the vertical component. It is clear, from Fig. 6 that at frequencies higher than ~ 14 Hz an abnormally high amplification at Bucharest is present, which is reflected to the shape of the spectra too. We used an average Q -value $Q(f) = 600f^{0.39}$ for both Bucharest and Iasi stations, where Q_0 was derived from the work of Radulian et al. [9] and we additionally corrected the Bucharest records using the transfer function from H/V . The revised spectra are shown in Fig. 7. Peak ground accelerations were improved. Spectral shapes and amplitudes for both stations were considerably improved but discrepancies still continue to exist at Bucharest station for high frequencies, beyond the engineering range of interest.

To further check our results, we calculated the pseudo-velocity spectrum at Bucharest station and compared it to attenuation relationships proposed by Theodoulidis and

Papazachos [37] for intermediate depth earthquakes. We found that for high frequencies (> 6 Hz), the simulated PSV spectrum falls within $\pm 1SD$ of the predicted PSV values for the given distance and magnitude.

4.2. 22 January, 2002 Karpathos island event (M_w 6.1)

As it is shown in Fig. 5, the Karpathos earthquake ground motions were generally well reproduced by the synthetic data, both in amplitude and shape for almost the entire frequency range of interest. Only at station APE, the simulated spectra predict higher values at high frequencies. The kappa value and the site amplifications functions used in our simulation were representative for rock sites. Small discrepancies at peak acceleration values or at the amplitude of the spectra could be ascribed to site-specific characteristics that were not taken into account.

5. Conclusions and discussion

We simulated acceleration time histories and Fourier amplitude spectra recorder during the 30 May 1990 Vrancea (Romania) and the 22 January 2002 Karpathos island (Greece) intermediate focus earthquakes, using the stochastic finite-fault modelling technique [13–15]. We employed average amplification functions estimated for rock, stiff soil and alluvium sites, but to obtain better simulations, we performed specific site conditions study for two stations in Romania. The results both for Vrancea and Karpathos island earthquakes were satisfactory.

From our study, some interesting features are worth noticing. For the Romanian earthquake, the largest peak ground accelerations were recorded at the most distant stations (Bucharest, Iasi) along the strike of the fault in a NW–SE direction, whereas at the closer stations (Vrancea, Birlad, Istrita), the peak amplitudes were lower by almost

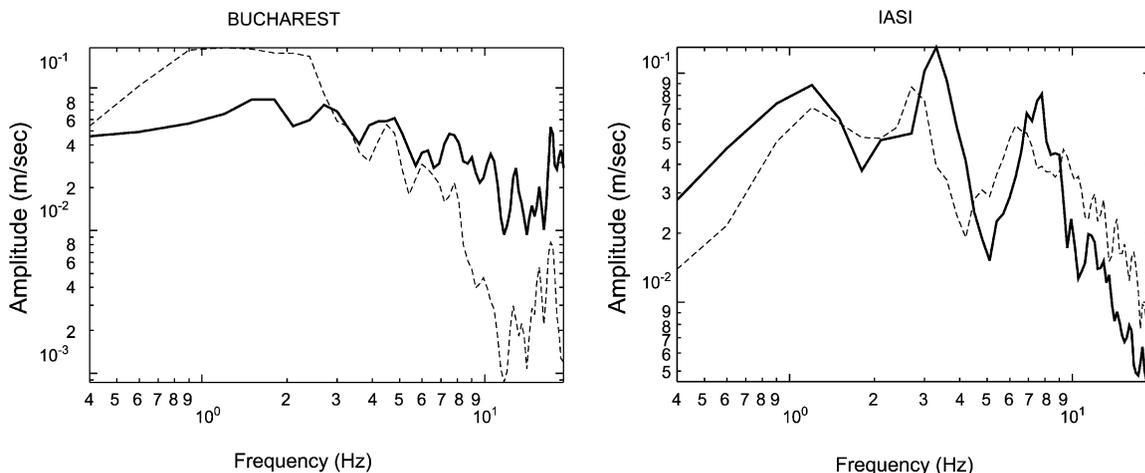


Fig. 7. Observed (continuous line) and simulated (dashed line) Fourier spectra for Bucharest and Iasi stations after incorporating site-specific amplification function for Bucharest station and new attenuation (Q) quality factors for both stations.

a factor of 2. In the Aegean Sea, this was not the case, where the peak acceleration values were observed at the closest to the epicentre stations.

In Romania, anisotropy of attenuation (in terms of Q -value) and specific site conditions had to be taken into account in order to predict the observed records both in shape and amplitude. A different Q -value along the NE–SW strike direction of the fault was assumed compared to the Q -value assumed for the stations distributed along the normal to the fault direction. Furthermore, site-specific amplification function using H/V ratio technique was used to obtain the transfer function and correct the simulated spectra at the station of Bucharest. Usually this analysis can significantly improve the shape of the Fourier spectra but usually underestimates true amplifications [38,39]. In the Aegean Sea, on the contrary, a single value for the attenuation operator and the gross characterization of the site were adequate in order to obtain very good simulation results.

The shape and the frequency content of the two events are also different in respect of peak acceleration values. The peak values for the Romanian event are observed at a narrow frequency band (2–4 Hz approximately) well within the range of frequency resonance for the majority of high storey residential buildings, whereas in the case of the Aegean Sea event, the peak acceleration values have repeated maxima for several cycles between 2 and 7 Hz, approximately.

Intermediate depth focus earthquakes are a threat both to Romania and Greece and we should pay special attention to their characteristics especially in view of the development of cities with high storey constructions.

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