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Stochastic Simulation of Strong-Motion Records from the 15 April 1979 (M 7.1) Montenegro Earthquake

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Abstract Acceleration time histories, recorded during the destructive 15 April 1979 (**M** 7.1) Montenegro earthquake, have been simulated using a stochastic modeling technique for finite faults proposed by Beresnev and Atkinson (1997, 1998a). In this approach, the ground-motion amplitudes are simulated as a summation of stochastic point sources. The length of the fault was taken as 70 km and its width as 25 km, and the fault plane was divided into 13 $\times$ 5 elements. The applied methodology is tested against its ability to predict site-specific strong-motion records by the incorporation of mean frequency–dependent site-amplification factors, based on a gross characterization of the site class. The results show that the overall agreement between stochastic and recorded waveforms and spectra is quite satisfying. Nevertheless, significant discrepancies exist at certain stations, implying that site-amplification functions play an important role in the simulation process. A repetition of the simulations combined with the use of site-specific amplification function estimated by the horizontal-to-vertical ratios technique improved the fit to the observed time histories and spectra.

Introduction

On 15 April 1979, at 06:19:40 UTC, a strong earthquake of **M** 7.1 occurred near the coast of Montenegro (in the former Yugoslavia). According to several authors (e.g., Kociaj, 1980; Boore *et al.*, 1981; Kanamori and Given, 1981; Karakaisis *et al.*, 1984; Baker *et al.*, 1997), the fault-plane solution of the mainshock and the spatial distribution of its aftershocks imply that this earthquake involved thrust faulting on a plane striking northwest–southeast, nearly parallel to the Adriatic coast and dipping northeast. The earthquake caused extended damage in Montenegro and in the northern district of Albania, especially along the Adriatic coasts. Ninety-four people were killed in Montenegro and 35 more in Albania, while the injured reached 1172 and 328, respectively. After the earthquake, 80,000 people were left homeless (Papazachos and Papazachou, 1997).

Strong-motion instruments located mainly within the state of Montenegro recorded the mainshock, as well as a significant number of foreshocks and aftershocks. These strong-motion data were recently disseminated by Ambraseys *et al.* (2000) as part of a European strong-motion database. The availability of these data, as well as the destructiveness of the 1979 event, provided the stimuli for simulating the recorded acceleration time histories. Since the information concerning the recording sites was rather limited, as is the case for most European strong-motion stations (Ambraseys *et al.*, 2000), we concentrated on the representation of the local site responses. Therefore, we first used mean amplification factors based on a gross characterization of the site geology, and next we employed site-specific amplification functions estimated by horizontal-to-vertical (H/V) ratios.

The technique used in this study for the simulations of strong-motion records is the stochastic finite-fault technique of Beresnev and Atkinson (1997, 1998a, 1999). In this method, the finite source is represented by a rectangular plane, which is subdivided into a certain number of elements (subfaults). Each subfault is treated as a point source, and each subevent has an ω-squared spectrum. The ground motion at an observation point is obtained by summing the contributions over several subfaults. A simple kinematic model of the Hartzell (1978) type is used to simulate the rupture propagation, which is assumed to start at the hypocenter and radially propagate from it. Propagation effects are empirically modeled by using the observed regional dependence of ground-motion amplitudes and duration on distance.

Data

Data used in the present study include the rock and stiff soil records of the 1979 Montenegro event contained in the European strong-motion database (Ambraseys *et al.*, 2000). Twenty-four accelerograms are used, obtained from five three-component stations installed at rock sites and three stations at stiff soil sites. The classification of the sites is based

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on Boore *et al.* (1993), and the information on near-surface geology stems from the European strong-motion database.

The recording instruments are analog accelerographs (Kinematrics SMA-1), installed at distances ranging from 16 to 105 km with respect to the epicenter of the examined earthquake. The acceleration time histories from the analog recording instruments were digitized at 100 samples/sec and bandpass filtered (0.1–25 Hz) using an eighth-order elliptical filter (Ambraseys *et al.*, 2000). The distribution of the strong-motion stations used in this study is shown in Figure 1, together with the epicenter of the mainshock and its focal mechanism given by Baker *et al.* (1997). Information on the installation sites is given in Table 1. Station names are those adopted in the European strong-motion database.

In the European database, data for the 1979 Montenegro mainshock were available for three more stations; however, the information concerning these recording sites was not adequate to classify the local geology according to Boore's scheme. Therefore, we decided not to simulate the specific records.

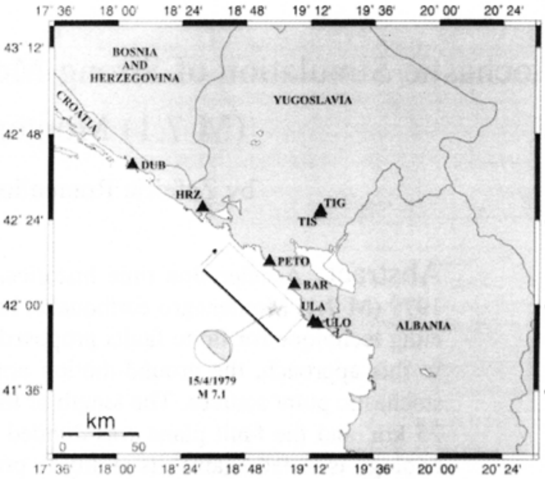

Figure 1. Regional map showing the epicenter (star) of the 1979 Montenegro earthquake and the sites of the recording stations (triangles) used in this study. The focal mechanism of the mainshock is also shown, as well as the fault plane employed to model the source of the earthquake.

Modeling Parameters

In the methodology of Beresnev and Atkinson (1997, 1998a) modeling of the finite source requires information on the orientation and the dimensions of the fault plane, as well as information on the dimensions of the subfaults and the location of the hypocenter. All the parameters used are summarized in Table 2. The orientation of the fault model used in the present study is derived from the focal mechanism of the 1979 Montenegro mainshock, estimated by Baker *et al.* (1997). The dimensions of the fault were chosen based on the spatial distribution of the aftershocks that occurred during the first two hours after the mainshock (Kociaj, 1980; Sulstarova and Lubonja, 1980). According to the aforementioned studies, the length of the seismic fault is equal to 70 km, while its width is 25 km. The selected fault model is depicted in Figure 1.

The discretization of the fault was done in such a way that the corner frequency of the subsources, f_c, would lie below the frequency range of interest (in our case, below 0.25 Hz). Corner frequency, f_c, is linked to subfault dimension, Δl, through the relation

$$f_c = \frac{\left(\frac{yz}{\pi}\right)\beta}{\Delta l}, \tag{1}$$

where β is the shear-wave velocity, y is the ratio of rupture velocity to β, normally set to a value of 0.8 (Beresnev and Atkinson, 1997), and z is the product of sfact and 1.68, a value that holds for a standard rupture. The parameter sfact 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 (Beresnev and Atkinson, 1997). A value of sfact equal to 1.0 corresponds to a standard rupture, while lower values imply slower slip and vice versa. We tested different values of sfact within the range 0.7–2.0 and found that the best match between simulated and observed spectra stands for sfact $= 0.9$. An f_c value of 0.25 Hz gives a minimum subfault size of $\Delta l = 5.2$ km. Based on this value, the target fault was divided into 13×5 elements.

Regarding the depth of the hypocenter, there is significant controversy among the published articles since it ranges from 1 to 22 km (e.g., Kociaj, 1980; Boore *et al.*, 1981; Karakaisis *et al.*, 1984; Baker *et al.*, 1997). We employed the depth of 12 km given by Baker *et al.* (1997) as a mean solution. Nevertheless, we also tested other values for the hypocenter and concluded that even though this parameter can lead to significant discrepancies in the strong-motion simulation of near-field stations, it does not affect the average accuracy of the predictions.

The material properties are described by density, ρ, and shear-wave velocity, β, which were given the values 2.7 g/cm^3 and 3.4 km/sec, respectively.

Another important input parameter of the employed methodology is the stress parameter $\Delta\sigma$. Since $\Delta\sigma$ is known with very large uncertainties for past events and even larger for future ones, we decided to keep its value fixed at 50 bars (Kanamori and Anderson, 1975), following the suggestion of the writers of the simulation code used (Beresnev and Atkinson, 1997). After all, a fixed value of this parameter primarily affects the number of elementary sources that need to be summed in order to conserve the seismic moment of the target event and not the radiation amplitudes (Beresnev and Atkinson, 1997).

Table 1
Information on the Installation Sites of the Strong-Motion Stations Used in this Study*

Code	Station Name	Country	Epicentral Distance	Lat. (°N)	Long. (°E)	Foundation Category	No. Earthquakes
BAR†	Bar, Skupstina Opstine	Yugoslavia	16	42.095	19.101	stiff soil	5
ULA†	Ulcinj, Hotel Albatros	Yugoslavia	21	41.919	19.221	rock	3
ULO†	Ulcinj, Hotel Olimpic	Yugoslavia	24	41.911	19.249	stiff soil	10
PETO†	Petrovac, Hotel Oliva	Yugoslavia	25	42.204	18.948	stiff soil	4
TIS	Titograd, Seismoloska Stanica	Yugoslavia	55	42.43	19.261	rock	
TIG	Titograd, Geoloski Zavod	Yugoslavia	56	42.442	19.264	rock	
HRZ†	Herceg Novi, O.S.D. Pavicic	Yugoslavia	65	42.457	18.531	rock	3
DUB	Dubrovnic–Pomorska Skola	Croatia	105	42.656	18.091	rock	

*Ambraseys *et al.* (2000)
† Stations for which site-specific amplification functions were computed.

Table 2
Modeling Parameters for the Application of the Simulation Method

Parameter	Montenegro Earthquake
Fault orientation	strike 316°, dip 14°
Fault dimensions (km)	70 × 25
Mainshock moment magnitude (**M**)	7.1
Stress parameter (bars)	50
Subfault dimensions (km)	5.4 × 5.0
Subfault moment (dyne cm)	1.0×10^{25}
Number of subfaults	65
Number of subsources summed	50
Subfault corner frequency	0.25 Hz
Crustal shear-wave velocity (km/sec)	3.4
Crustal density (g/cm^3)	2.72
Distance-dependent duration term (sec)	duration equal to source rise time
Geometric spreading	$1/R$
$Q(f)$	$100.0 \times f^{0.8}$
Windowing function	Saragoni-Hart
Kappa operator (κ)	0.035 (rock), 0.05 (stiff soil)

The propagation model includes parameters for the geometric spreading, the anelastic attenuation, and the near-surface attenuation, as well as site-amplification factors.

For the geometric attenuation we applied a geometric spreading operator of $1/R$, and the anelastic attenuation was represented by a mean frequency–dependent quality factor for the Aegean and the surrounding area, $Q(f) = 100f^{0.8}$ (Hatzidimitriou, 1993, 1995), derived from studies of *S*-wave and coda-wave attenuation in northern Greece.

The effect of the near-surface attenuation was also taken into account by diminishing the simulated spectra by the factor $\exp(-\pi f \kappa)$ (Anderson and Hough, 1984). The kappa operator (κ) was given the values 0.035 and 0.05 at rock sites and stiff soil sites, respectively (Margaris and Boore, 1998).

No specific information exists regarding the distribution of slip during the 1979 Montenegro mainshock. Therefore, we exploited the capability of the simulation code to produce random normally distributed slip. According to Beresnev and Atkinson (1998b), this choice does not considerably affect the accuracy of predicting either the mean of expected ground motion at several sites or its standard deviation.

Site-Amplification Factors

The performance of the stochastic simulation method of Beresnev and Atkinson (1997, 1998a) has been previously tested against its ability to predict strong ground motion from large earthquakes at sites with varying response characteristics (Beresnev and Atkinson, 1998b, c; Castro *et al.*, 2001). In the aforementioned works, site amplification was taken into account by employing site-specific amplification factors, which were estimated from weak-motion recordings, either by variations of the inversion procedure proposed by Andrews (1986) or by the H/V ratios technique.

Unfortunately, information concerning the actual amplification factors is rare in many regions. This limitation could be overcome by the use of mean amplification factors based on a gross characterization of the site class, if these are proved to adequately predict the strong ground motion on average. Therefore, in the present work, we validate the performance of the Beresnev and Atkinson (1997, 1998a) method in predicting strong ground motion at different sites, to which we assign mean amplification factors. The classification of the sites was performed following the scheme proposed by Boore *et al.* (1993), which is based on the measured or estimated average shear-wave velocity to a depth of 30 m (V_{S30}). According to this scheme, the examined sites that recorded the 1979 Montenegro mainshock have been classified as rock sites ($V_{S30} > 750$ m/sec) and stiff soil sites (360 m/sec $< V_{S30} <$ 750 m/sec). Information on the values of V_{S30} at the examined sites was also taken from the European strong-motion database. Unfortunately, no soft-soil sites (V_{S30} <360 m/sec) were included in the number of sites with known geology regarding the 1979 Montenegro event. The amplification factors employed for each site category are given by Boore and Joyner (1997).

In order to compare the results of the simulation method when employing mean amplification factors with those produced by the use of site-specific amplifications, we estimated the latter at stations where three or more aftershock recordings of the 1979 sequence were included in the European strong-motion database. These stations are denoted by an asterisk at the right side of their name in Table 1. In addition, in the last column of Table 1 we show the number of events used. Site amplifications for these stations were derived using the H/V spectral ratios technique. The shapes of the estimated transfer functions and their standard deviations are shown in Figure 2. An interesting conclusion that stems from Figure 2 is that a large amplification (more than a factor of 2) may exist at most frequencies, even at stations such as ULA and HRZ that have been characterized as rock sites. This implication becomes even more important if we take into account the large uncertainties in the estimation of the mean transfer function at each site and the fact that the H/V ratios technique usually underestimates true amplifications (Bard, 1998; Castro *et al.*, 2001). Due to these shortcomings of the H/V ratios technique, we do not expect the simulated spectrum to perfectly match the observed spectrum in amplitude, though a better match is expected in shape.

Results

In Figure 3 we compare the recorded and simulated accelerograms and Fourier spectra amplified by the mean amplification factors of Boore and Joyner (1997) at the sites of the eight stations presented in Table 1. The frequency range of this study is 0.25–15.0 Hz, the lower limit being set by the filtering of the data. The observed spectrum at each site was calculated as the geometric 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 observed acceleration components (top two traces). The simulated traces (bottom trace) consist of random horizontal components and have the same sampling interval as the recorded traces to which they are compared (0.01 sec). Next to each time trace we also present the corresponding peak value of the acceleration for reasons of comparison.

Peak ground accelerations are generally well reproduced, except from stations PETO and HRZ where an overestimation of more than a factor of 2 is observed. The amplitudes of the observed spectra are generally very well matched in the high-frequency range ($>\sim4$ Hz) at all the examined stations. Nevertheless, large discrepancies are observed in the lower frequency range at most stations, which do not seem to depend on the source-station distance. The overestimation of the simulated spectra at low frequencies is observed at all three stiff-soil sites (BAR, ULO, PETO) and at two rock sites (ULA and HRZ). This misfit could be due to inadequacies in the representation of the source or the

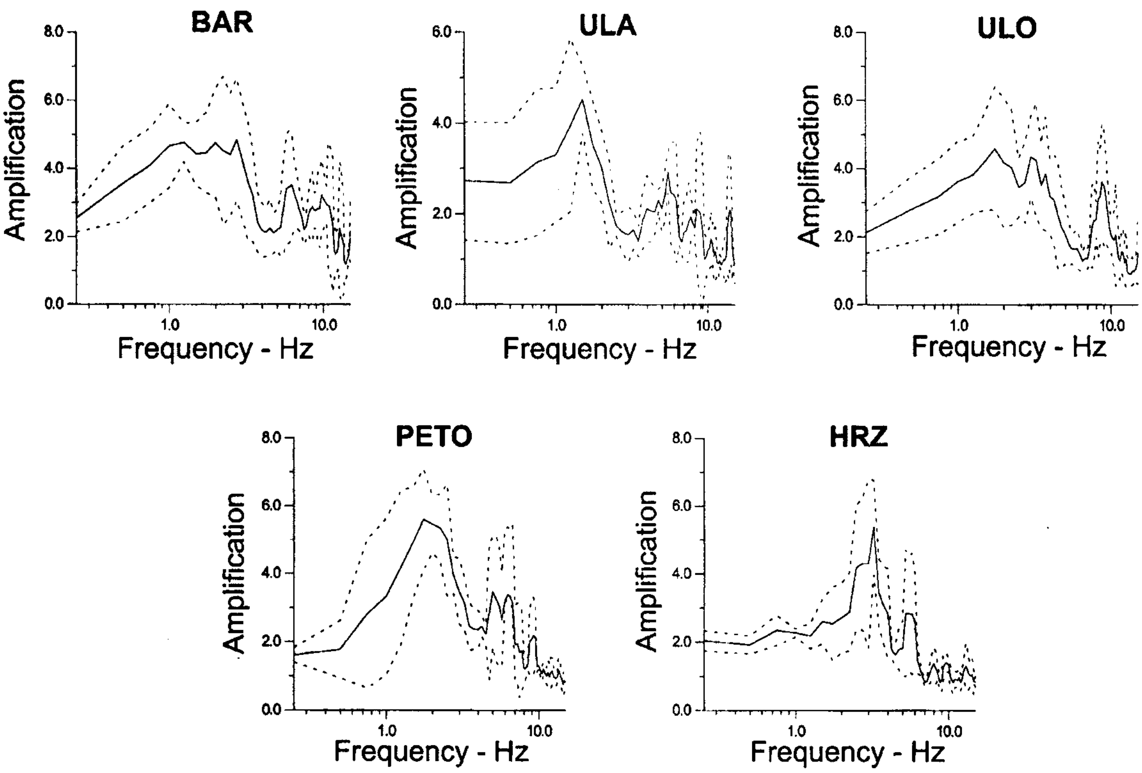

Figure 2. Site-amplification functions estimated using H/V spectral ratios from aftershocks of the 1979 Montenegro event. Dashed lines indicate± 1 standard deviation.

local site amplifications. Since the employed source model worked very successfully for stations TIS, TIG, and DUB, we attributed these differences between inferred and true spectra to site responses.

In Figure 4a we present the model bias, defined as the ratio of simulated to observed Fourier spectrum, (Abrahamson *et al.*, 1990; Schneider *et al.*, 1993; Atkinson and Boore, 1998; Beresnev and Atkinson, 1998b), averaged over all stations. Dashed lines show ± 1 standard deviation. From Figure 4 we conclude that the mean ratio of simulated to ob-

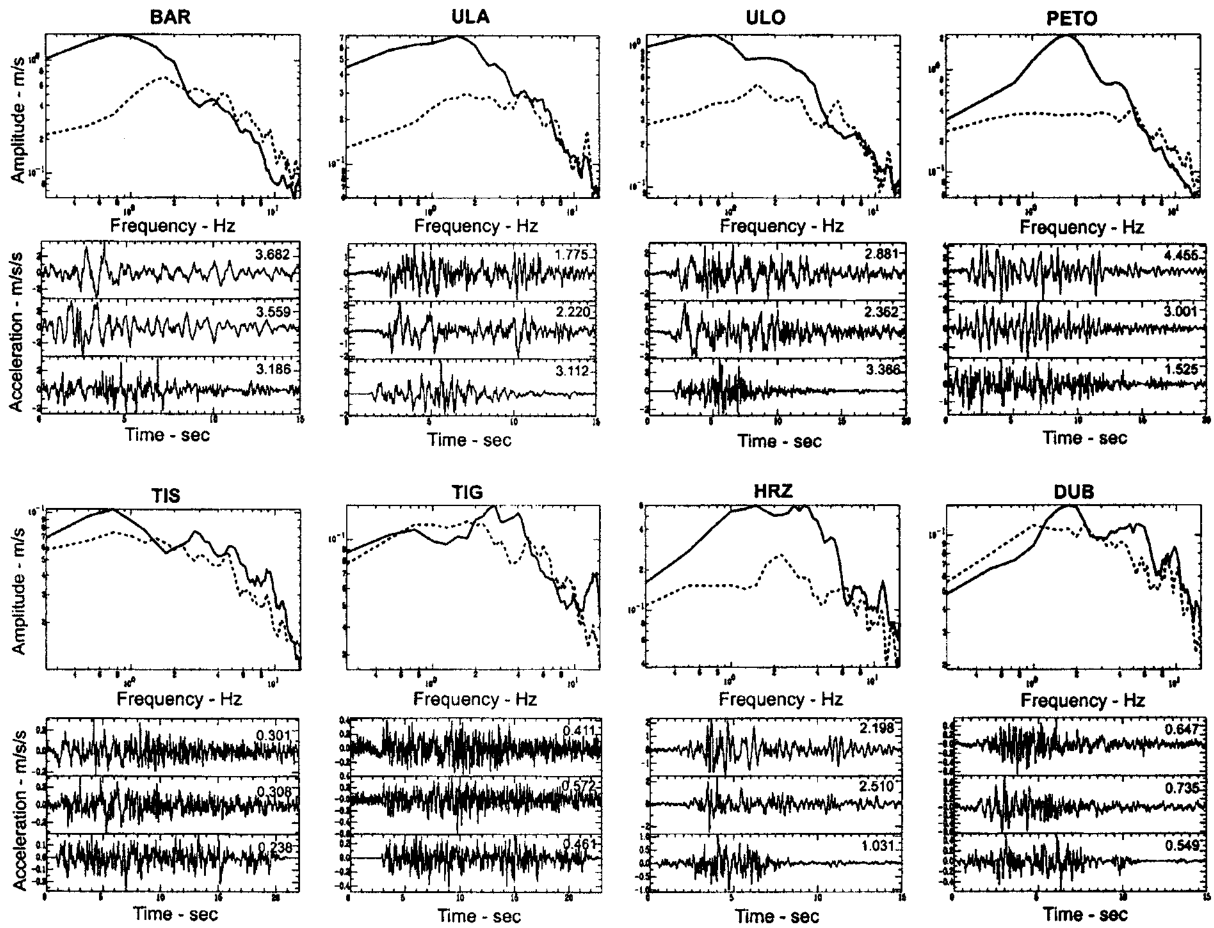

Figure 3. Recorded and simulated acceleration time histories and Fourier spectra at the eight stations shown in Figure 1. The observed and simulated spectra are shown by the continuous and dashed lines, respectively. Below the spectra, the upper two traces are the recorded horizontal components (north–south and east–west), whereas the lower trace is the simulated random horizontal component. The peak value of acceleration is also shown for each trace.

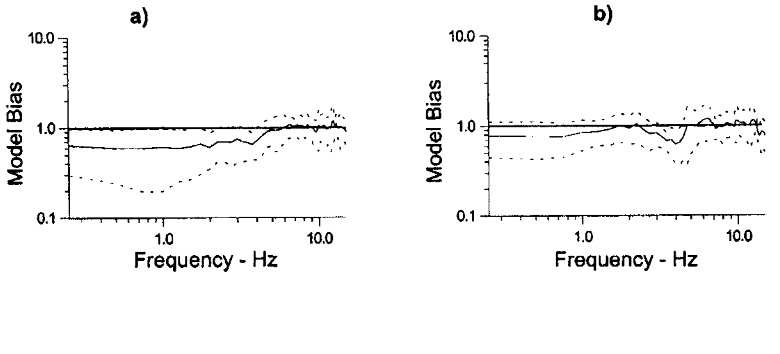

Figure 4. Model bias showing the ratio of simulated to observed spectrum, averaged over the eight stations depicted in Figure 1. (a) Simulated spectra have been amplified according to mean amplification factors. (b) Simulated spectra at five out of eight stations have been amplified according to the site-specific amplification functions shown in Figure 2. Dashed lines indicate ± 1 standard deviation of the mean.

served spectra is very close to unity for frequencies larger than about 4 Hz, whereas at lower frequencies there is a systematic overestimation, that, however, is less than a factor of 2. This means that the employed mean amplification factors adequately predicted the observed strong ground motions on average, although the uncertainties in predictions at individual sites are relatively large.

In order to see whether the differences between simulations and observed motions are due to inadequate amplification of the spectra, we repeated the simulations at all stations studied (BAR, ULA, ULO, PETO, and HRZ) using the site-specific amplification functions shown in Figure 2. The new synthetic spectra are compared to the observed spectra in Figure 5. The accuracy in the predictions is much better this time, and this can also be deducted by the model bias shown in Figure 4b. The mean is much closer to unity at low frequencies than in Figure 4a, while the band defined by standard deviation is much narrower.

A very successful result of the aforementioned applications is the surprisingly accurate simulations of the spectra recorded at stations HRZ (with the site-specific amplification factors) and DUB (with the mean amplification factors), where a clear effect of the source directivity appears (higher spectral levels and higher corner frequencies).

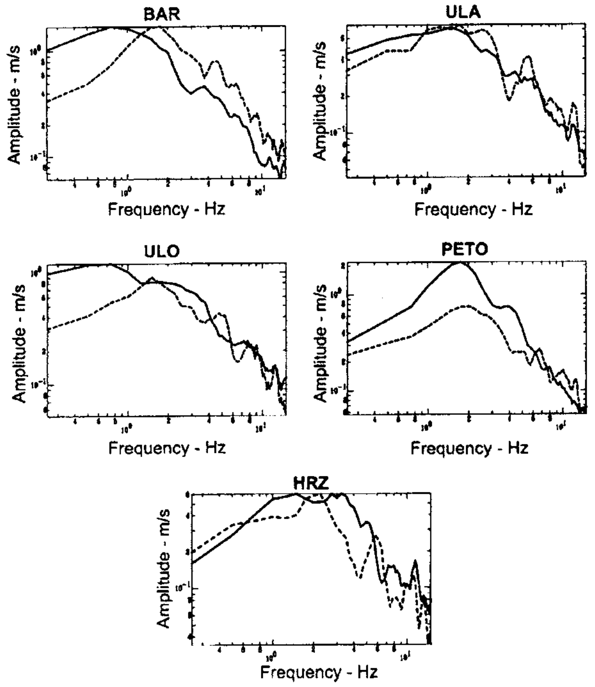

Figure 5. Recorded and simulated Fourier spectra for five (out of eight) stations. Simulations have been repeated incorporating site-specific amplification functions.

Conclusions

We simulated acceleration time histories and Fourier spectra recorded during the 1979 Montenegro mainshock, using the stochastic method for finite faults proposed by Beresnev and Atkinson (1997, 1998a, 1999). We initially employed mean amplification factors estimated for rock and stiff-soil sites (Boore and Joyner, 1997) to account for the effects of local response. The results show a satisfactory match between simulated and observed peak ground accelerations and Fourier spectra, although significant discrepancies were observed at individual stations. Large differences between synthetics and recordings were basically limited to the low-frequency part of the spectrum ($<\sim$4 Hz).

We repeated the simulations at five stations for which we were able to estimate site-specific amplification functions based on H/V ratios. The estimated transfer functions were used to account for site response instead of the initially employed mean amplification factors. The matching between synthetics and recordings was better at all five stations. Remaining differences could be attributed to the uncertainties in the estimation of mean transfer functions, the incapability of the H/V ratios technique to reveal the absolute values of amplification, or to other factors such as topography or complexity of the source. At BAR, specifically, we should not exclude the possible nonlinear behavior of the ground, as the station is at a small distance (16 km) from the epicenter of the earthquake, where the levels of strong ground motion increased and the *S*-wave velocity averaged over the top 30 m is relatively small (V_{S30} = 408 m/sec).

As a conclusion, the applied simulation method in combination with a very simplified representation of local site responses adequately predicted observed strong ground motions during the 1979 Montenegro event on average. This result is quite encouraging for applications of the stochastic method at sites where response characteristics are poorly known, at least at sites that reveal *S*-wave velocities similar to those of the examined sites. Nevertheless, more attention must be paid to the uncertainties in the predictions at individual sites and especially at sites that reveal very low *S*-wave velocities (soft-soil sites), where amplifications are expected to be much more complicated and phenomena such as nonlinearity in local responses often occur. A better level of accuracy in predicting future ground motions, however, can be obtained by using reliable site-specific amplification functions.

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