ABSTRACT

We simulated strong motion records from the Umbria-Marche, Central Italy earthquake (Mw 6) of September 1997 using a frequency-dependent S-wave radiation function. We compared the observed acceleration spectra, from strong-motion instruments located in the near field and at regional distances, with those simulated using the stochastic modeling technique of Beresnev and Atkinson (1997, 1998), and modified to account for a frequency dependent radiation pattern correction. By using the frequency-dependent radiation function previously obtained by Castro et al. (2006) we reduced the overall fitting error of the acceleration spectra by about 9%. In general, we observed that the frequency-dependent radiation pattern correction has a small effect on the spectral amplitudes compared with site effects, which is an important factor controlling the strong-motion records generated by the 1997 Umbria-Marche earthquake. In addition, we modeled the observed ground-motion records using the dynamic corner frequency model of Motazedian and Atkinson (2005) to reproduce the directivity effects, reducing the average error of the spectral amplitudes by 24%. We concluded that although the frequency-dependent radiation pattern correction affects the frequency content of the spectral amplitudes simulated, site and directivity effects are more relevant.
Introduction

Stochastic modeling techniques for finite faults (e.g. Beresnev and Atkinson, 1997) simulate the high-frequency ground-motion amplitudes by summing stochastic point sources. In this process the S-wave radiation pattern is considered as independent of frequency and a constant average value is used to model the source spectra. However, recent studies of S-wave radiation pattern, using local earthquakes in Japan (Takenaka et al., 2003) and Central Italy (Castro et al., 2006), show that at low frequencies (f<0.5 Hz) the observed radiation pattern is similar to that expected from a double-couple source. However, at higher frequencies (f>0.5 Hz) the S-wave radiation pattern varies randomly with frequency.

Several source studies have pointed out that the S-wave radiation pattern is not constant at high frequencies (e.g. Liu and Helmberger, 1985; Vidale, 1989; Takenaka et al., 2003). These studies suggest that the complexity of the source rupture process and the heterogeneity of the crust may contribute to the frequency-dependent radiation pattern.

Because the stochastic modeling techniques simulate high-frequency ground-motion amplitudes assuming that the radiation pattern is constant, we evaluate in this paper the effect of incorporating a frequency-dependent S-wave radiation function in the stochastic finite-fault technique of Beresnev and Atkinson (1997). We also analyze the dynamic corner frequency model introduced by Motazedian and Atkinson (2005) to simulate ground motion. In this model the energy radiated by each subfault is controlled by the rupture history and the corner frequency is a function of time.

In particular, we simulated strong-motion records from the Umbria-Marche, Central Italy earthquake (Mw6) of September 1997 using a frequency-dependent S-wave radiation function determined empirically by Castro et al. (2006). We choose this event because the source parameters are well known from previous studies. This earthquake, also known as the 1997 Colfiorito earthquake, ruptured a fault segment nearly 12 km long (De Martini and Valensise,
The extent of the rupture area of nearly 50 km was determined by Amato et al. (1998) and Deschamps et al. (2000). The normal faulting focal mechanism was well constrained using long-period wave forms (Ekstrom et al., 1998), and the slip distribution obtained by forward and inverse modeling of GPS measurements and SAR interferograms (Stramondo et al., 1999; Hunstad et al., 1999; Salvi et al., 2000). Based on the distribution of PGA at the triggered strong-motion stations, Castro et al. (2001) reported evident effects of rupture directivity toward the northwest from the epicenter. In particular, the PGA at Nocera Umbra (NOC), located in the direction of rupture propagation, is more than a factor of two the value predicted by the empirical regression model proposed by Sabetta and Pugliese (1987).

The strong-motion records from stations located in the near field have been also previously modeled by Berardi et al. (2000) and Castro et al. (2001) using a stochastic simulation approach. Figure 1 shows the location of the main event of the 1997-1998 Umbria-Marche sequence and the distribution of strong-motion stations used by Castro et al. (2001) and also in this paper. The acceleration time records were corrected for baseline, instrument response and band-pass-filtering to avoid long-period biases and high-frequency noise with band-pass frequencies ranging between 0.05 and 27 Hz. Thus, at low frequencies the acceleration spectra are reliable above 0.05 for station NOC, above 0.18 for CLF, ASI and BVG and above 0.55 for MNF and MAT.

**Frequency Dependent Radiation Pattern**

Castro et al. (2006) used local earthquakes registered during the 1997-1998 Umbria-Marche aftershock sequence to analyze the frequency dependence of the S-wave radiation pattern. Most of the earthquakes analyzed are normal fault events that occurred at shallow depths (H<6.3 km). They separated source and path effects using a spectral inversion technique and then the
radiation pattern was isolated from other source related effects by calculating the fraction of SH-wave contribution to the total S-wave energy following the same procedure used by Takenaka et al., (2003).

\[
R_{SH}(f) = \frac{S_{SH}^2(f)}{S_{SV}^2(f) + S_{SH}^2(f)}
\]

(1)

Where \( S_{SH}(f) \) and \( S_{SV}(f) \) are the amplitudes of the SH- and SV-waves source functions, respectively, obtained from the spectral inversion. \( R_{SH}(f) \) can be considered a measure of the radiation pattern of SH waves.

Castro et al. (2006) found that in general the low frequency SH energy approaches that expected from a double-couple source. In particular, at 0.34 Hz the fraction of SH energy is about the same, but at higher frequencies (\( f > 0.5 \) Hz) the radiation pattern varies randomly with frequency.

Figure 2 shows the average SH radiation pattern function obtained by Castro et al. (2006) using 22 aftershocks of the sequence with magnitudes ranging between 3.3 and 5.6. This function shows a maximum between 2 and 4 Hz and then varies randomly with frequency. It is also interesting to note that the mean value in the frequency band shown (0.3-24 Hz) is 0.6, consistent with previous estimates of the average S-wave radiation pattern (Boore and Boatwright, 1984).

The average fraction of SH energy estimated by Castro et al. (2006) can be projected on the NS-EW directions using the take-off angle of the strong-motion station to be modeled. We did that to be able to model the observed NS and EW spectral components. Figure 3 shows the projected SH-wave energy for the six stations modeled. These functions represent the S-wave radiation pattern at each recording site. In general, the values of \( R_{SH} \) vary between 0.5 and 0.9.
Stochastic Finite-Fault Modeling

Frequency Dependent Radiation Pattern

We simulated the strong-motion records of the closest sites to the fault that generated the 1997 Colfiorito earthquake using the stochastic finite-fault method developed by Beresnev and Atkinson (1997, 1998). This method combines the stochastic ground-motion technique of Boore (1983) with a kinematic model to simulate rupture propagation.

As mentioned before, the Colfiorito earthquake has been previously simulated by Castro et al. (2001) using a constant radiation pattern correction of 0.6 and the modeling parameters listed in Table 1. To analyze the effect of the frequency dependent radiation pattern on the ground-motion simulations, we used the same source parameters (Table 1) and the radiation pattern functions shown in Figure 3. Another source parameter that controls the simulated ground motion amplitudes is the radiation-strength factor \( sfact \), we used \( sfact=0.9 \) for our simulations.

To account for the observed high-frequency decay of the spectral amplitudes, we used the cut-off filter originally introduced by Boore (1983) to model S-wave acceleration spectrum. A cut-off frequency \( f_c=15 \) Hz was used for all the sites analyzed (see Table 1).

The fault plane was divided into 60 subfaults with a length of 1.2 km and a width of 1.5 km. The hypocenter was located in the southern end of the fault plane and to account for inhomogeneous slip distribution, we increased the slip weight on subfaults located near the hypocenter. The slip distribution was constrained based on inversion results of geodetic data (Hunstad et al., 1999; Salvi et al., 2000). The faulting mechanism and fault geometry were defined using the source parameters reported by Ekstrom et al. (1998) from the CMT solution.

To account for site amplification, we used the site-transfer functions for stations Colfiorito (CLF) and Nocera (NOC) reported by Scognamiglio (1999) and Marra et al. (2000), respectively, using the standard spectral ratio technique. For the rest of the stations the site
amplification factors were estimated using horizontal to vertical spectral ratios (Castro et al., 2001). The amplification factors displayed by these site functions vary from about 14 for station NOC, located on alluvial deposits, to 1.6 for station MNF, which is on rock (Figure 4). Station ASI is also on rock, CLF and BVG on lacustrine deposits, and MAT on alluvial deposits (Luzi et al., 2005). The records simulated were also corrected for attenuation using the relation $Q(f) = 77 f^{0.6}$ obtained by Castro et al. (2000 and 2002) with earthquakes from the 1997 Umbria-Marche sequence and a geometrical spreading function of the form $G(r) = 1/r$, where $r$ is the hypocentral distance. For consistency we used the same geometrical spreading function for the simulations.

The distance-dependent duration was also estimated in the previous study for each site by calculating the observed average duration of both horizontal components records from aftershocks of the sequence.

Dynamic Corner Frequency

Motazedian and Atkinson (2005) introduced a new approach to the stochastic finite-fault model of Beresnev and Atkinson (1998) based on a dynamic corner frequency. In this new model the frequency content of the simulated ground motion of each subfault is controlled by the rupture history and the corner frequency is a function of time. The main advantage of the dynamic corner frequency model is that the high frequency energy radiated is conserved, regardless of subfault size, and consequently it is possible to use an arbitrary constant subfault size. Thus, the new method has a wider magnitude range of application than previous versions of the stochastic finite-fault models. There are two main model parameters: the stress drop that controls the high-frequency spectral amplitude level and the percentage of pulsing area that controls the level of spectra at low frequencies. The pulsing area parameter controls the percentage of active subfaults during the rupture process and thus contributing to the dynamic corner frequency.
We used this new model to simulate the strong-motion records generated by the 1997 Colfiorito earthquake. We used the same model parameters as before (see table 1) and try different values of stress drop. Figure 5 shows the observed acceleration spectra at CLF, the closest station to the source, and the spectral amplitudes calculated using a constant radiation pattern (left frame) and using the frequency dependent radiation pattern (Figure 3). We made the same calculations for all stations to calculate the model bias and the average error.

To quantify the fit between observed and simulated acceleration spectra, we define a model bias as:

\[
E(f) = \frac{1}{n} \sum_{i=1}^{n} \log \left( \frac{S(f)_{\text{obs}}}{S(f)_{\text{sim}}} \right)_i
\]

Where \( n \) is the number of stations modeled and \( S(f) \) the acceleration spectra. We also define the average error within the frequency band used to simulate the spectra as:

\[
\varepsilon = \frac{1}{m} \sum_{j=1}^{m} |E(f_j)|
\]

Where \( m \) is the number of frequencies considered in the analysis.

Figure 6 and Table 2 show the values \( E(f) \) and \( \varepsilon \) obtained for different values of stress drop. When using a constant radiation pattern we have to reduce the stress drop to 100 bars to fit the observed high-frequency amplitude level and to 50 bars when we use the frequency dependent radiation pattern (see right frame of Figure 5). We also try different values of the percentage of pulsing area, finding the best fit with a value of 35%, consistent with the slip distribution reported by Hunstad et al. (1999).
Results

Figure 7 compares the observed (solid line) and the simulated acceleration spectra (discontinuous lines). We also compare the spectral amplitudes simulated using a constant radiation pattern for both the standard finite-source model of Beresnev and Atkinson (1997, 1998) (dotted lines) and the dynamic corner frequency model of Motazedian and Atkinson (2005) (black dots) with those obtained using the frequency-dependent radiation pattern functions in the standard finite-source technique (dashed lines). In general, the dynamic corner frequency model provides the best fit, particularly at low frequencies (0.1-0.5 Hz) for stations CLF, BVG and MAT. It is also interesting to note that for NOC, located in the direction of rupture propagation, neither model reproduce the observed amplitudes that well, suggesting the need of an additional directivity correction, as reported by Castro et al. (2001).

Figure 8 shows the model bias calculated with Equation (2) for the static corner frequency model of Beresnev and Atkinson (1997) with constant radiation pattern (dotted line) and using the frequency dependent functions (dashed line). In this model the corner frequency remains constant during the whole rupture history. For the first the average error calculated with Equation (3) equals 0.194 and for the latter 0.176. Although the overall error is smaller when a frequency-dependent radiation is used, at high frequencies (f> 4 Hz) the constant radiation pattern value of 0.55 gives a better fit. The dots in Figure 8 are the model bias calculated using the dynamic corner frequency model with constant radiation pattern. As explained above, in this model the corner frequency is a function of time. Note that at low frequencies this model provides better fit than the frequency-dependent radiation model and at high frequencies a better fit than the static corner frequency model with constant radiation pattern. We calculated an average error of 0.146 using the dynamic corner frequency which is also smaller than that of the other two models.
Figure 9 displays the observed acceleration records (N-S components) and the simulated time series obtained with the dynamic corner frequency model. In general, the peak acceleration levels resulting from the simulation are similar to those observed. We also improve the fit of the acceleration spectra (compare solid line and dots in Figure 5) for the whole frequency band analyzed (0.1-25 Hz). In particular for station Colfiorito (CLF), the closest station to the source, the simulated spectral amplitudes follow closely the observed average at low and high frequencies. This trend is in general clearer in Figure 8, where we plotted the model bias of the three models.

**Discussion and Conclusions**

Because the dynamic corner frequency model conserves the high-frequency energy radiated by the source, regardless of the subfault dimension, a stress drop of 100 bars was enough to model the 1997 Umbria-Marche earthquake. We calculated the model bias using all the stations modeled (right frame in Figure 6) and found that $E(f)$ (Equation (2)) takes values closer to zero for 100 bars, and the average error (Table 2) is also smaller. In contrast, the static corner frequency model requires a stress parameter of 200 bars (see left frame in Figure 6 and Table 2). The use of the frequency-dependent radiation pattern function (Castro et al., 2006) reduces the overall fitting error of the acceleration spectra by 9.3 %. However, if we consider the magnitude of the site amplification of the stations analyzed, the effect of the radiation pattern seems small. For instance, station Nocera (NOC) and Colfiorito (CLF) have amplification factors of 14 near 7Hz and 6 near 1Hz, respectively (Castro et al., 2001). In addition, station NOC, located in the direction of rupture propagation, also shows important directivity effects at low frequencies. At the frequency band where the site effect is minimum ($f< 1.0$), the directivity effect at NOC can increase the spectral amplitudes by a factor of at least 4 times at frequencies below 0.3 Hz (see Figures 4 and 6).
In conclusion, the frequency-dependent radiation pattern correction proposed in this study has a small effect on the simulated spectral amplitudes, compared to site and directivity effects, which are the most important factors controlling the strong-motion records generated by the 1997 Umbria-Marche earthquake.

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Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE)

División Ciencias de la Tierra

Departamento de Sismología

km 107 Carretera Tijuana-Ensenada

22860 Ensenada, Baja California, México

raul@cicese.mx

(R.R.C.)

Istituto Nazionale di Geofisica e Vulcanologia,

Sezione di Milano,

Via Bassini 15, 20133 Milano, Italia

pacor@mi.ingv.it

(F.P., G.F., D.B., G.Z., L.L.)
**Ekstrom *et al*. (1998)
**TABLE 2.** Estimates of average error (see Equation (3)) obtained using a constant radiation patterns (Rsh=0.55) and using the frequency dependent function shown in Figure 2.

<table>
<thead>
<tr>
<th>Radiation Pattern</th>
<th>Stress drop</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 bars</td>
</tr>
<tr>
<td>$Rsh=0.55$</td>
<td>0.191</td>
</tr>
<tr>
<td>$Rsh(f)$</td>
<td>0.121</td>
</tr>
</tbody>
</table>
Figure 1. Location of the main event (star) of the 1997-1998 Umbria-Marche sequence and the distribution of strong-motion stations used (triangles). The focal mechanism shown was obtained by Ekstrom et al. (1998).

Figure 2. The continuous line represents the average SH-wave radiation pattern function obtained by Castro et al. (2006) using local events from the Umbria-Marche sequence, Central Italy. The dashed lines are the average ± 1 standard deviation.

Figure 3. S-wave radiation pattern projected on the horizontal plane (NS-EW). The numbers inside the frames are the take-off angle used at each station.

Figure 4. Site amplification functions of the stations analyzed. The functions of CLF and NOC were estimated by Scognamiglio (1999) and Marra et al. (2000), respectively, using standard spectral ratios. The rest of the stations were determined by Castro et al. (2001) using H/V spectral ratios. The letters inside the frames indicate the site conditions reported by Luzi et al. (2005): Ac= lacustrine deposits with thickness greater than 30m; Bc= alluvial deposits with thickness less than 30 m; Dc= rock.

Figure 5. The solid line is the observed acceleration spectra at station CLF and the dashed lines the simulated spectra for different stress drop values. Left frame shows the spectra calculated using a constant radiation pattern of 0.55 and right frame using the frequency-dependent radiation pattern shown in Figure 3.
Figure 6. Values of model bias estimated with all stations using a constant radiation pattern correction of 0.55 (left frame) and using the frequency dependent radiation pattern (right frame) for different values of stress drop. Solid line corresponds to 50 bars, dotted lines to 100 bars and dashed line to 200 bars.

Figure 7. Acceleration spectra obtained at the stations analyzed. Solid lines are the observed amplitudes, dashed lines are simulated amplitudes using the finite-source model of Beresnev and Atkinson (1997,1998) and the radiation pattern functions shown in figure 3; dotted lines are simulated amplitudes using the same model but with a constant radiation pattern of 0.55; and the black dots are the simulated amplitudes using constant radiation pattern and the dynamic corner frequency model of Motazedian and Atkinson (2005).

Figure 8. Model bias calculated for the three models: the static corner frequency model with a constant radiation pattern of 0.55 (dotted line), that with the frequency-dependent radiation pattern (dashed line) and the dynamic corner frequency model with constant radiation pattern (dots).

Figure 9. Ground acceleration time series. On the left are the observed North-South components and on the right side the simulated ground acceleration obtained using the dynamic corner frequency model.
FIGURE 1
FIGURE 2
FIGURE 3

[Diagrams showing radiation patterns for CLF, NOC, ASI, BVG, MNF, and MAT with corresponding values for each pattern: γ = 54.1, γ = 64.0, γ = 74.5, γ = 75.2, γ = 77.7, γ = 78.2]
FIGURE 4
FIGURE 5
FIGURE 6
FIGURE 7
FIGURE 9