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COMBINED EFFECT OF BASIN RESONANCE AND SOURCE DIRECTIVITY: IMPLICATIONS FOR LONG PERIOD HAZARD IN THE APENNINES, CENTRAL ITALY

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ABSTRACT

During the three strongest shocks of the 1997 Umbria-Marche, central Italy, seismic sequence, long-period ($T > 1$ s) spectral ordinates showed large variations in intermountain basins in the Apennines. In particular, at a strong-motion station in the Rieti plain, about 65 km south of epicenters, long-period response spectra during the Mw 5.6 and 5.7 shocks had larger amplitudes than the Mw 6.0 ones; in contrast, in the Gubbio basin, about 40 km northwest of the epicenters, the Mw 6.0 shock had spectral ordinates exceeding those of the Mw 5.6 and 5.7 shocks by more than a factor of 10 at long periods. Since focal mechanisms were similar for the causative earthquakes and the difference in magnitude and source-to-receiver-path is small, these observations can only be explained in terms of a different source directivity. The availability of a rock station on the Gubbio basin edge and other moderate-magnitude earthquakes of the same seismic sequence allows us to separate the local amplification term from the varying contribution of source directivity for the different shocks. Their combination is responsible for long-period ground displacements significantly larger than 10 cm at Mw 6.0 and 40-km source distance. Since source directivity is a very recurrent feature for normal-faulting earthquakes of the Apennines (evident during the recent L'Aquila earthquakes even at magnitudes as small as 3), these results arise a concern for many intermountain basins located in a geographical position favorable to a significant hazard increase due to source directivity. Furthermore, the performance of different Ground Motion Prediction Equations has been explored as well as of corrections based on various source directivity models.

INTRODUCTION

In the framework of several research projects supported by the Italian Department for Civil Protection [DPC] under an agreement with the Istituto Nazionale di Geofisica e Vulcanologia [INGV], the strong-motion data recorded in Italy by different institutions were collected and organized in an electronic archive. Seismic events as well as instrument and site metadata were documented and stored, and the raw recordings were individually processed in order to obtain reliable estimates of ground motion waveforms and acceleration response spectra. Details on procedures and data are described in the reports of the Project S4 (*Italian Strong Motion Database*, coordinated by Roberto Paolucci and Francesca Pacor, available at <http://itaca.mi.ingv.it/ItacaNet>), that realized the final version of the Italian Accelerograms Archive (ITACA), from where strong-motion recordings of earthquakes occurred in Italy can be freely downloaded and the metadata about stations and earthquakes can be easily accessed. In the activity framework of Project S4, ground-motion prediction equations (GMPEs) were also assessed for the Italian territory based on the available data. Bindi et al. (2009a) used a site classification with three classes according to geological and geotechnical information relative to the uppermost layers: rock (class 0, rock outcrops or deposits with thickness less than 5 m); shallow alluvium (class 1, deposits with thickness lower than or equal to 20 m); and deep alluvium (class 2, deposits with thickness greater than 20 m), where alluvium refers to deposits with shear-wave velocity between 400 and 800 m/s. Di Alessandro et al. (2008 and 2011) proposed an alternative classification based on the horizontal-to-vertical spectral ratio (HVSr) of 5%-damped response spectra: in their approach, classes depend on the predominant period of the average HVSr of each station. Both these groups of authors investigated inter-event and inter-station variability (see also Bindi et al.,

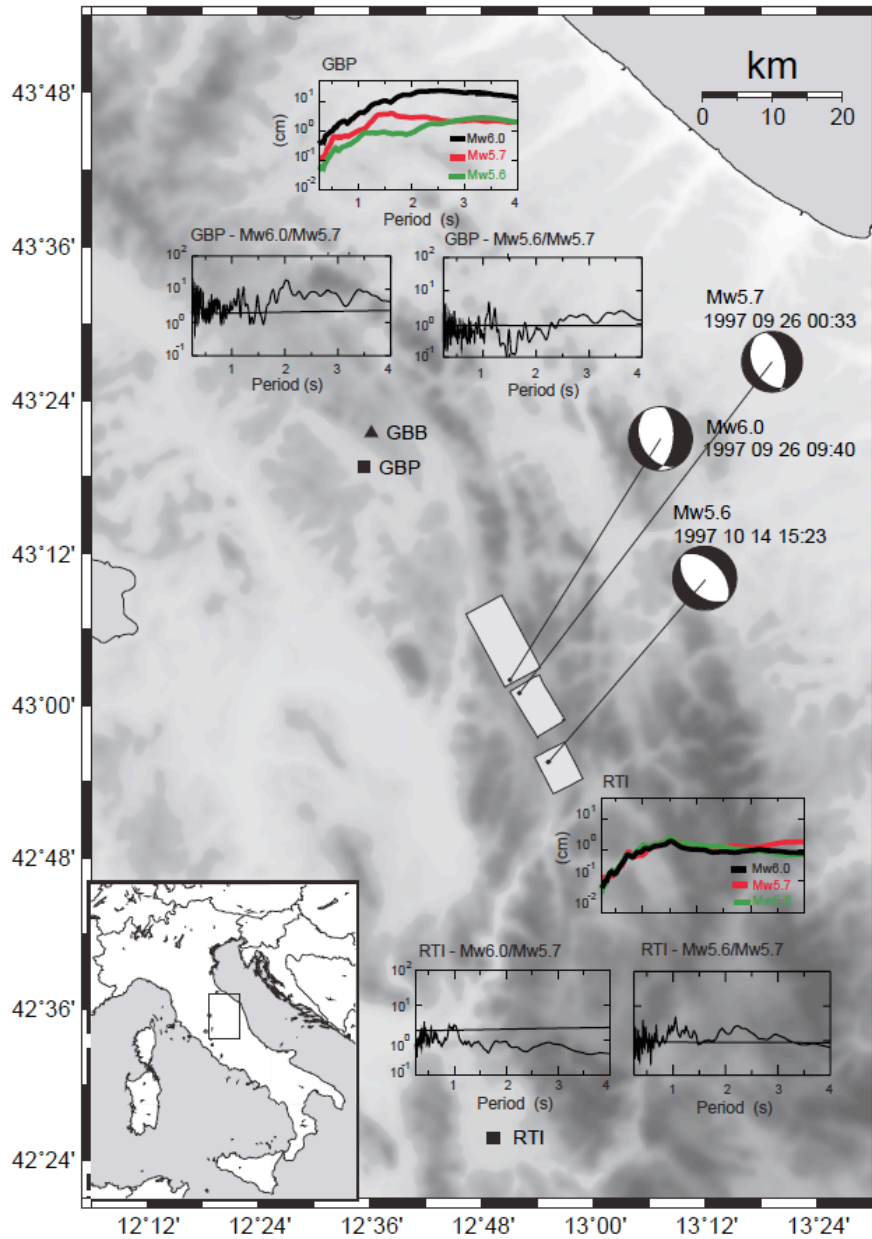


Fig. 1. Faults and focal mechanisms of the three strongest shocks of the 1997 Umbria-Marche seismic sequenc (DISS Working Group, 2010). Three panels show ground motion variations at the two accelerometric stations of GBP, in the basin of Gubbio, and RTI, in the basin of Rieti. Apparently, there is no consistency between the two stations and between magnitudes at each station.

2009b), and both agreed in indicating the stations of GBP (Gubbio Piana) and RTI (Rieti) among those characterized by the largest residuals, being largely underpredicted by statistical expectations (see Deliverable 8 of Project S4, available at <http://itaca.mi.ingv.it/ItacaNet>).

These two stations are installed in intermountain basins in central Apennines (Figure 1). For both of them, the near-surface velocity structure was investigated through geophysical methods based on inversion of surface wave dispersion. At the GBP site *in situ* downhole measurements were also performed. Estimated V_{s30} values of GBP and RTI are 224 and 170 m/s, respectively (Deliverable 10 of Project S4, available at <http://itaca.mi.ingv.it/ItacaNet>). The basin of Gubbio, where GBP is installed, was the subject of many papers (Mirabella et al., 2004; Pacor et al., 2007; Bindi et al., 2009c; Parolai et al., 2009) dealing diffusely with the basin origin, its

structure and seismic response. However, a less discussed issue is the reason of the large variability of spectral ordinates compared to the expected curves, even for many earthquakes of the same seismic sequence where small changes in hypocentral positions and focal mechanisms cannot justify huge amplitude fluctuations. Interestingly, if we consider the residuals of the same earthquakes as computed for the accelerograms recorded at GBP and RTI we see an opposite behavior. The two stations were struck by the Umbria-Marche earthquakes from southeast and north-northwest, respectively (see Fig. 1), and this difference in source backazimuth will drive our approach to data interpretation in terms of source directivity.

Table 1. List of the earthquakes used in this study (x indicates the record availability)

Date	Time	Lat	Lon	Mw	GBP	GBB	RTI
1997 09 26	00:33	43.02	12.89	5.7	x		x
1997 09 26	09:40	43.00	12.84	6.0	x	x	x
1997 10 14	15:23	42.90	12.93	5.6	x		x
1997 10 03	08:55	43.04	12.28	5.2	x	x	
1997 10 06	23:24	43.02	12.84	5.4	x	x	x
1998 04 03	07:26	43.18	12.74	5.1	x	x	

In this study, we have analyzed and compared the ground shaking of the two basins. We have demonstrated that the observed variations have to be ascribed to the source directivity of the investigated Umbria-Marche earthquakes. We have also sought for corrective theoretical factors able to reproduce observations. In this perspective, we have explored the performance of the directivity models proposed by Spudich and Chiou (2008) and by Rowshandel (2006 and 2010) implemented for one of the two faults (the Mw 6.0 one) that, according to Cultrera et al. (2009), showed the strongest role of directivity on azimuthal variations of ground motion.

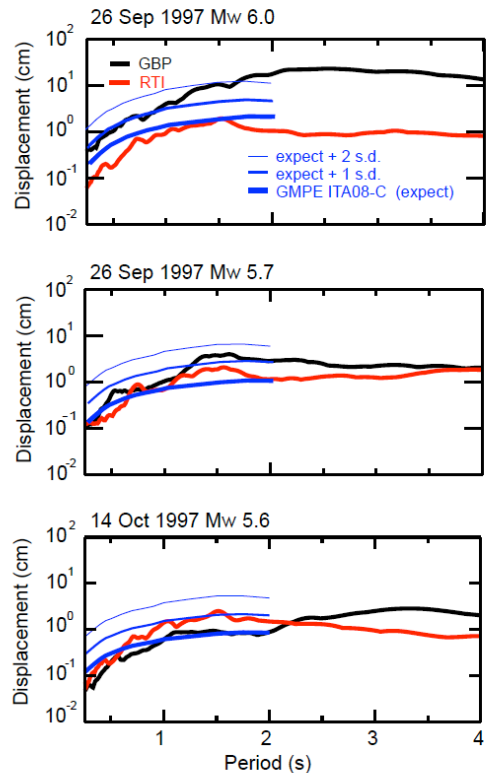


Fig. 2. Displacement spectral ordinates are compared to expectations by Bindi et al. (2009a) derived from Italian strong motion data, Class 2 (thick soft deposits). In some cases, observations exceed expectations by more than 2 s.d.

DATA

We have considered 6 moderate-magnitude earthquakes of the 1997-1998 Umbria-Marche seismic sequence (Table 1). The digital accelerometer of GBP recorded all of them. At RTI, the analog accelerometer was triggered only by 4 events. Variations of ground shaking were huge during the seismic sequence: for the sake of example, the insets of Fig. 1 show ground motion observations of GBP and RTI for the three largest Umbria-Marche shocks. Focal mechanism and source-to-receiver-path were similar for these earthquakes (Fig. 1), therefore event-by-event variability is expected to be small. In contrast, we see that the ground motion difference between events is very large and not consistent with the small difference in magnitude. The insets close to each of the two stations depict displacement response spectra at Mw 6.0, 5.7, and 5.6 and the spectral ratio of Fourier amplitudes at each station between earthquake couples. We can observe that, during the Mw 6.0 shock, displacement response spectra of GBP exceed 20 cm at periods $T > 2$ s but are about a factor of 10 smaller during the Mw 5.6 and 5.7 shocks (uppermost inset of Fig. 1). This difference is well beyond the expectation due to the difference in magnitude: the inset below GBP response spectra (in the left-hand side) shows the spectral ratio between the two strongest events (Mw 6.0 and 5.7) in terms of Fourier Amplitude Spectra of horizontal motions (geometric mean) compared to the ratio of the Brune (1970) source spectra. At periods $1 < T < 4$ s, this spectral ratio is significantly larger than expected on the basis of the Brune model. The third panel of GBP (on the right-hand side) shows that the Mw 5.6 curve goes below the Mw 5.7 one for $1 < T < 2$ s, but this could be due to the different source distance. Interestingly, RTI shows the opposite behavior: the lowermost inset of Fig.1 shows that the spectral ratio between the two strongest events is much smaller than expected on the basis of the magnitude difference. Moreover, at RTI the three largest shocks show comparable displacement ordinates, of the order of few centimeters, for $T > 1$ s.

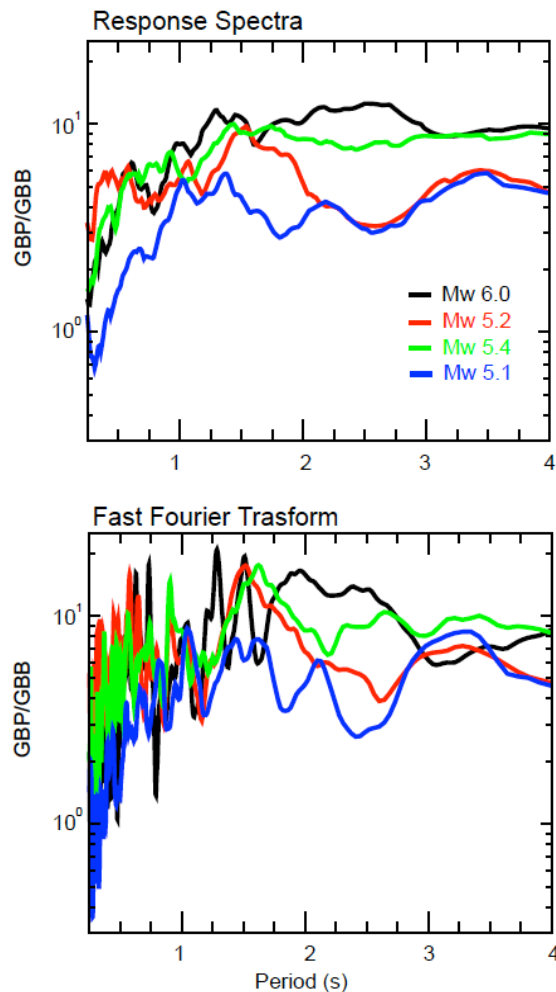


Fig. 3. Soft-to-stiff site spectral ratio in the basin of Gubbio, computed for moderate-magnitude earthquakes of the 1997 Umbria-Marche seismic sequence (Table 1). The fundamental basin resonance is around 2 s, according to Bindi et al. (2009c).

Pino et al. (1999) studied azimuth variations of source spectra of the 1997 Umbria-Marche seismic sequence in an EGF approach. They enhanced the important role of source directivity during the strongest shocks. Cultrera et al. (2009) investigated the effect of source directivity on high-frequency ground motions of the Umbria-Marche seismic sequence. Their conclusions were substantially similar: Pino et al. (1999) attributes a strong source directivity to the Mw 6.0 earthquake toward northwest whereas the two Mw 5.6 and 5.7 shocks showed shorter source durations toward south-southeast. Cultrera et al. (2009) observed the strongest azimuthal variations during the Mw 6.0 and 5.6 earthquakes whereas the effects of the Mw 5.7 shock were less pronounced. Having in mind these conclusions, we have checked the possible role of directivity on observed displacement response spectra of GBP and RTI for the Mw 6.0, 5.7 and 5.6 earthquakes (Fig. 2). Panels of Fig. 1 seem to confirm that the effect of source directivity during the Mw 5.7 shock was somewhat smaller than the Mw 5.6 one, or in a different direction. Cifelli et al. (2000) describe the intensity effects caused in Rome (that is along the same direction of Rieti from the epicenter) by the Mw 5.6 event, confirming that it was the most distinctly felt shallow earthquake in Rome among the shallow Umbria-Marche earthquakes.

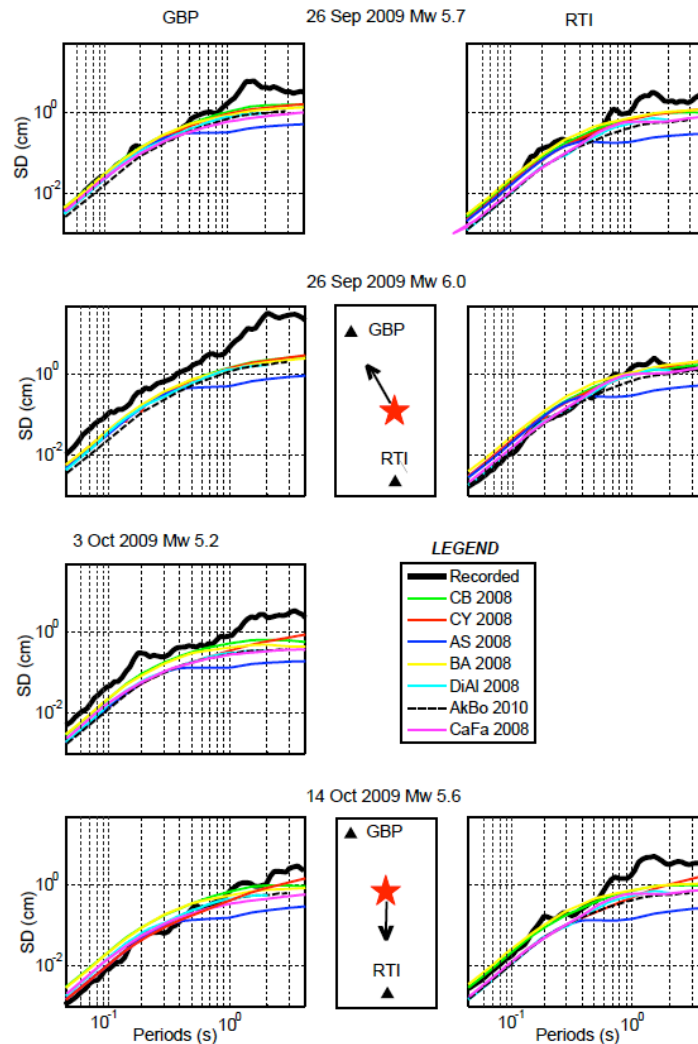


Fig. 4. Comparison between pseudo-displacement response spectra of GBP and RTI and global GMPEs (Abrahamson and Silva 2008; Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008; Cauzzi and Faccioli, 2008) as well as from pan-European (Akkar and Bommer, 2010) or Italian data (Di Alessandro et al., 2008 and 2011). When source directivity plays the strongest role (the Mw 6.0 and 5.6 shocks, as shown by the sketch in middle panels) the two stations show the largest and smallest discrepancy from predictions depending on their source backazimuth.

Fig. 2 compares displacement response spectra with the expected GMPEs by Bindi et al. (2009a), derived from soft sites on thick sedimentary deposits in Italy. Theoretical curves are drawn with the +1 and +2 s.d. bands above expectations. The most evident feature of Fig. 2 is that displacements of GBP are beyond the +2 s. d. curve for $T > 1.5$ s when extra amplitudes are caused by directivity (upper panel), whereas they are within the +1 and +2 s. d. bands when source rupture propagates in the opposite direction (bottom panel). The Mw 5.7 event (middle panel), which probably had a weak directivity, has an intermediate behavior at long periods, with displacement ordinates satisfactorily fitted by the mean + 1 s. d. curve, with the only exception around $T = 1.5$ s where the + 1 s. d. curve is exceeded by GBP observations. Displacement response spectra of RTI, south of epicenters, are substantially fitted by its statistical expectation for the Mw 5.7 event, and are slightly below the expectation for the Mw 6.0 event that radiated in the opposite direction.

The opportunity of a rock station (GBB in Fig. 1, see Table 1) on the edge of the Gubbio basin allowed the estimate of the basin amplification at GBP. Fig. 3 shows the spectral ratio, in terms of both Fourier amplitude and response spectra, between the two stations. Although instrumented with an analogue accelerograph and then affected by a higher level of noise at short- and long-periods, GBB provides a useful rock reference to assess an empirical transfer function at the intermediate periods where the basin sediments resonate. Fourier and response spectra yield a quite consistent spectral ratio trend resulting in a ground motion amplification of about 10 at periods $1 < T < 2$ s.

At the end of this discussion, we can conclude that the amplification of GBP due to basin sediment excitation is large independently of source directivity: in the case of weak directivity, it is well fitted by the mean + 1 s.d. expectation curve of GMPEs by Bindi et al. (2009a). RTI is much closer to the prediction curve for thick-sediment class. When amplitudes are affected by source directivity, positive and negative variations can be very large. As a matter of fact, spectral ordinates exceed the mean + 2 s.d. curve for the Mw 6.0 main shock when GMPEs assessed from Italian data are used. However, the high level (> 20 cm) of displacement response spectra of GBP during this shock is far away to be predicted by any of the commonly used GMPEs in the world. Fig. 4 compares the recorded and predicted pseudo-spectral displacements for stations GBP and RTI for 4 moderate-magnitude earthquakes. A set of Global GMPEs (Abrahamson and Silva 2008; Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008; Cauzzi and Faccioli, 2008) as well as the one derived from pan-European data (Akkar and Bommer, 2010) are plotted in the panels. The predictive model by Di Alessandro et al. (2008 and 2011) is also included because derived for Italian accelerometric stations. We ensured consistency in referring the predicted spectral values to the geometric-mean of the horizontal components, by using the conversion factors proposed in Beyer and Bommer (2006), Boore et al. (2006), Boore and Watson-Lamprey (2007). The conclusion emerging from Fig. 4 is that, whatever GMPE is used, the discrepancy of observations from predictions is particularly large during the two earthquakes characterized by the strongest source directivity: the Mw 6.0 event amplifies the GBP deviation and vanishes the RTI one, and the opposite occurs during the Mw 5.6 earthquake.

IMPROVING PREDICTIONS WITH SOURCE DIRECTIVITY FACTORS

In order to investigate to what extent the large variations in ground motion spectral ordinates with respect to standard GMPEs could be ascribed to directivity effects, the source directivity models proposed by Spudich and Chiou (2008) and by Rowshandel (2006 and 2010) are applied to the Umbria-Marche mainshock (Mw 6.0) case, whose fault geometry and rupture information are extracted from the DISS database (DISS Working Group, 2010).

These directivity models require the hypocenter location and the entire extent of rupture to be specified. The models propose set of empirically determined correction factors to be applied to median models in order to obtain amplification (or de-amplification) factors. Being the Rowshandel (2010) and Spudich and Chiou (2008) models developed within the NGA project (<http://peer.berkeley.edu/ngawest>), their correction factors apply to either the average NGA GMPEs (the former directivity model only) or to the individual NGA GMPEs (both directivity models). For the sake of simplicity, here we present the results obtained applying the model by Spudich and Chiou (2008) for the Boore and Atkinson (2008) GMPE, which could be considered representative of the NGA models for the magnitudes investigated; for the Rowshandel (2006) model, we present the results for an “average directivity” referred to all the NGA models.

We did not implement the source directivity models by Abrahamson (2000) and by Somerville et al. (1997) because they do not provide coefficients for events with $M_w < 6$.

Figure 5 shows the implementation of the Spudich and Chiou (2008) model for our study. For this purpose, we computed the effect of the directivity for the Boore and Atkinson (2008) GMPE by considering a grid of 1023 points at spacing of 5 km and a period range between 0.75 and 4 sec.

The first three panels show the spatial variation of the parameters C (related to the Isochrone Velocity), R_{ri} (Scalar Radiation Pattern Amplitude) and IDP (Isochrone Directivity Predictor) as are defined in the paper by Spudich and Chiou (2008). The IDP values are controlled by the product of C and R_{ri} , whose spatial distribution is in turn controlled by the faulting mechanism (in our case normal) and the position of the nucleation point (in our case near the lower southeast tip of the fault). The empirical amplification factors f_D at

1, 2 and 3 s periods for the Boore and Atkinson (2008) GMPE are shown in the last three panels, respectively. The distribution of the amplification factors shows azimuthal variations and a weak dependence on distance up to 70 km from the source corresponding to the distance threshold of the model. The directivity is marked by a lobe towards North as due to the interaction of the nodal plane of the focal mechanism with the up-dip rupture propagation. As noticeable from the range of values in the contour plots scales, the amplification factors increase with period, and show a maximum value of 0.06 (in unit of the natural logarithm of g) at 3 sec. Such small value is associated with an increase of about 6% with respect to the response spectral amplitude at 3 sec of the Boore and Atkinson (2008) GMPE.

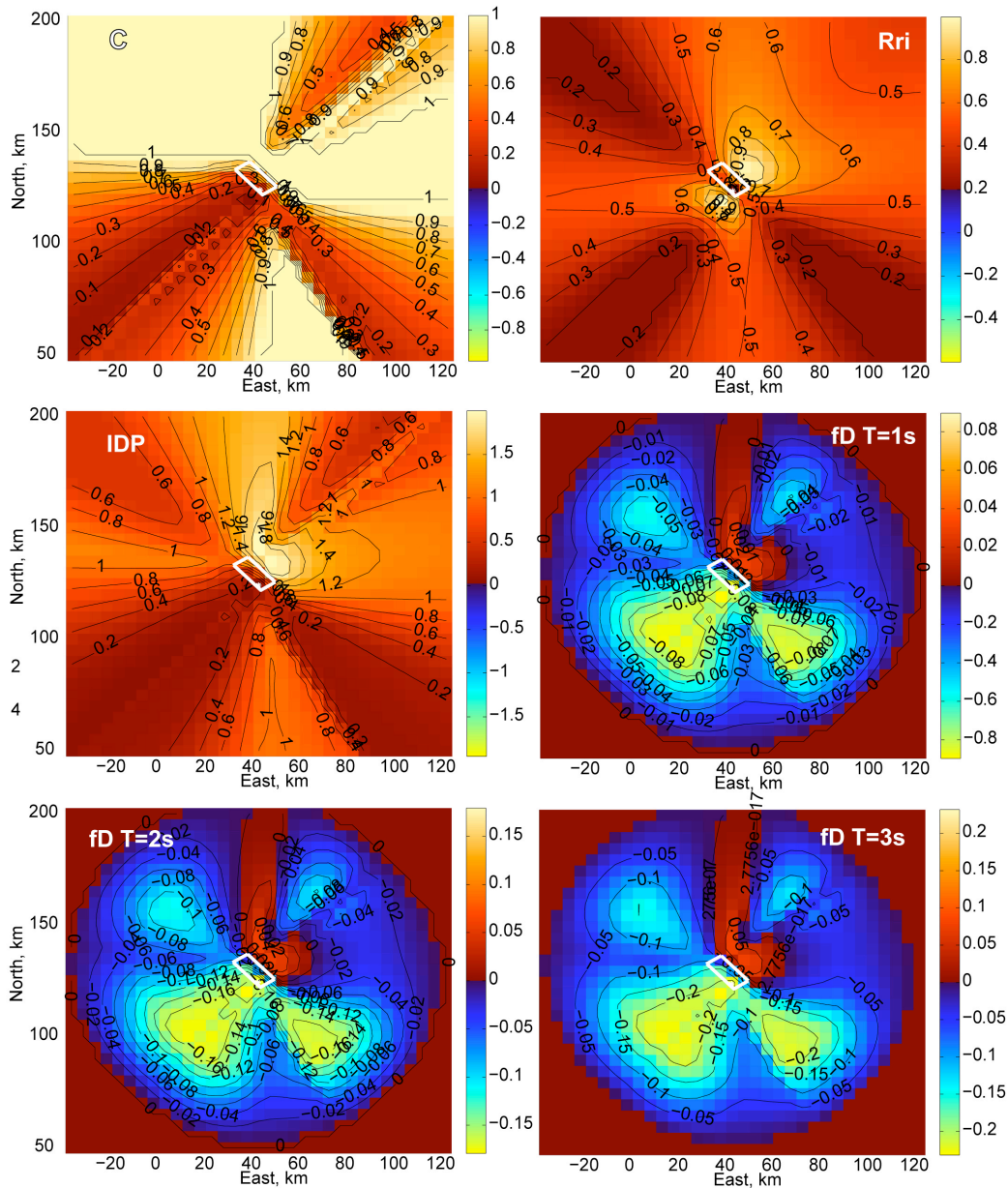


Fig. 5. Spatial variation of the parameters C , Rri , and IDP as defined in the Spudich and Chiou (2008) model, and amplification factors (f_D) due to source directivity at 1s, 2s and 3s. Distances in the plots are based on a generalized kilometric coordinate system.

The other models tested in this study are those proposed by Rowshandel (2006 and 2010) who investigates other directivity parameters on the base of rupture direction, or slip direction (rake), or a combination of them. The models are based on the original formulation of Somerville et al. (1997), who considers two distinct categories (strike-slip and dip-slip), and adopts, as directivity indicators, the angle between the direction of rupture and the direction of traveling waves from the source to the site (θ for strike-slip

faults and ϕ for dip-slip faults), and the fraction of ruptured length, s for strike-slip faults, or ruptured width d for dip-slip faults, that lies between the hypocenter and the site. For dip-slip faults,

$$Y = \left(\frac{d}{W} \right) \cos(\phi) \quad (1)$$

where W is the fault width. The models by Rowshandel (2006 and 2010) are capable of handling every type of rupture directions because they generalize both the aforementioned Y and ϕ terms by applying a surface integral over the fault for every receiver location. Additionally, the models retain some flexibility because the Y and ϕ parameters can be computed either with respect of the rupture direction or of the slip (rake) of the fault, or a combination of these two. The main directivity indicator in the Rowshandel's approach is therefore a function of the increment of the fault area that ruptures in a given direction, of the vector that defines the direction from the rupturing area increment to the site, of the source-to-site azimuth angle, and of the effectiveness of the rupturing area increment in influencing the ground motion at the site.

The Rowshandel (2010) model assumes a distance-dependency for the directivity factors, whose values tend to decay rapidly at magnitudes around 6. Thus this model is not applicable for the present study. However, the Rowshandel (2006) model, like the Somerville et al. (1997) one, does not include such distance-dependency. Therefore, it allows relatively large directivity effects also at large distance. The top panels in Fig. 6 show the directivity indicator distributions based on rupture direction, rake, and combined rupture direction and rake, while the bottom panels show the resulting percentage (%) changes in ground motions (SA2 – 2 sec, SA3 –

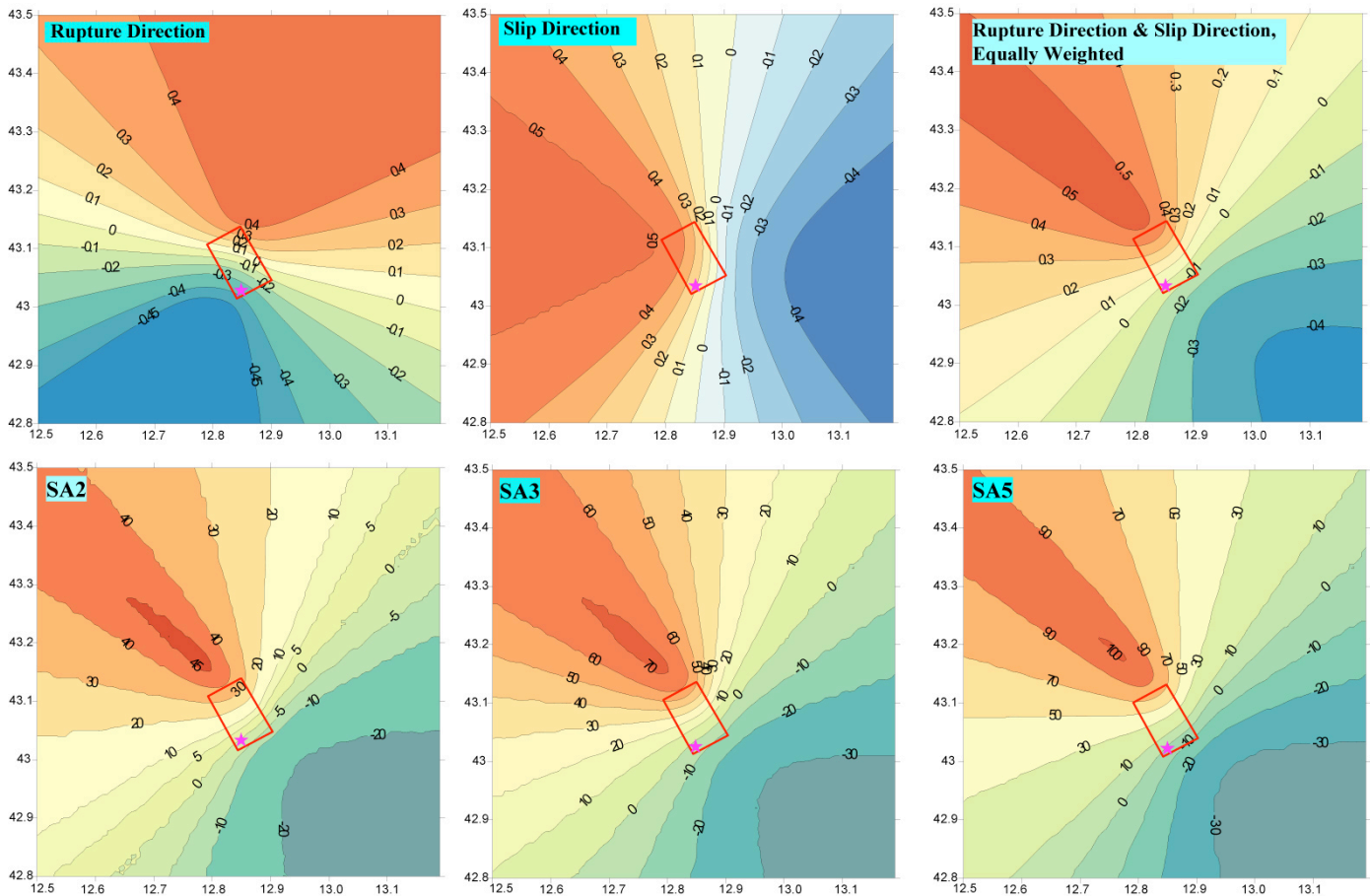


Fig. 6. (Top panel) Distribution of directivity indicator for the Rowshandel (2006 and 2010) models, based on: direction of rupture (left), direction of slip or rake angle (middle), and direction of rupture and rake angle, equally weighted (right). (Bottom panel) Distribution of average percentage change in ground motion for the Rowshandel (2006) model due to directivity based on the top-right model (combination of rupture and slip directions).

3 sec, and SA5 – 5 sec), assuming no-distance dependency (i.e., "average directivity") and combined effect of rupture direction and rake. In this case, the increment due to source directivity can be as large as 100% along strike in front of the rupture. This direction corresponds to the location of GBP station. As in the case of Spudich and Chiou (2008) model, the amplification increases with period meanwhile the directivity pattern remains unchanged. In the south azimuth, corresponding to RTI station, predicted deamplification is around 20-30% depending on the period.

DISCUSSION AND CONCLUSIONS

Recent earthquakes in the Apennines, when recorded by a significant number of instruments, showed evidence of recurrence of source directivity. This was observed by many authors at moderate magnitudes: Pino et al. (1999) and Cultrera et al. (2009) for some of the 1997 Umbria-Marche largest shocks ($5.6 < M_w < 6.0$); Gorini et al. (2004) for the 2002 Molise twin M_w 5.7 earthquakes; Akinci et al. (2010), Çelebi et al. (2010), Di Alessandro et al. (2011) for the 2009 L'Aquila M_w 6.3 mainshock. A paper in preparation demonstrates the evidence of source directivity during the 2009 L'Aquila seismic sequence in a broad magnitude range, even at magnitudes as small as 3. A similar finding is reported by Boatwright (2007) who stressed the persistence of source directivity at magnitudes $3.5 \leq M_w \leq 4.1$ in an earthquake cluster near San Ramon, California, and Lengliné and Got (2011) who analyzed repeating microearthquakes occurring in the San Andreas fault near Parkfield, at magnitudes as small as $1.0 < M_L < 3.1$.

In the Apennines, mostly for normal faults, source directivity is expected along the chain trend, and this is also the predominant orientation of intramountain sediment-filled basins (like the Gubbio one). In this paper, we demonstrate that the combination of these two factors may have important implications for the intensity of basin ground shaking. As a matter of fact, soft sites are characterized by a significant local amplification: a factor of 10 is frequently observed. When combined with source directivity, the deviation of observed ground motions from expectations of commonly used GMPEs of the seismic hazard practice can exceed 2 s.d. at moderate magnitudes.

We have used two different models of directivity correction for GMPEs in the case of a M_w 6.0 earthquake corresponding to the mainshock of the 1997 Umbria-Marche seismic sequence. We have observed large differences between the two models both in terms of pattern and amplitudes. The Rowshandel (2006) model seems to explain better the trend of our observations at GBP and RTI stations. However, the directive-to-antidirective variation given by this model (100% and -30%, respectively) is small compared to the one of real data that shows a spread of around 10. In principle, this could indicate that the Umbria-Marche earthquakes had an extent of source directivity larger than the "average directivity" inferred from the NGA data set, however statistics for normal-faulting earthquakes is poorer than for strike-slip ones.

The results of this study and the recent experience from the 2009 L'Aquila earthquakes suggest that in Italy source directivity plays an important role on ground motion variability at moderate magnitudes, and a significant improvement of GMPEs is potentially achievable, at least for normal-faulting earthquakes that provided the largest wealth of instrumental data so far.

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