Ground motion scaling in Eastern Sicily (Italy)

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ABSTRACT

We describe the characteristics of crustal wave propagation in Eastern Sicily by using the background seismicity of the area. We follow the approach described by Malagnini et al. (2000, 2002). Our data set consists of 106 earthquakes recorded by 9 three-component digital seismic stations between 1994-2001. We used only crustal events (depths shallower than 25 km), with local magnitudes ranging from 1.0 to 4.3, and hypocentral distances from 10 to 130 km.

Peak ground velocities from 1311 narrow bandpass-filtered waveforms are measured in the frequency range 1.0-16.0 Hz, and regressed to define crustal propagation, excitation and site characteristics, with respect to a reference station. A subsequent modeling effort is carried out, through the use of random vibration theory (RVT), for obtaining a quantitative evaluation of the apparent geometrical spreading g*(r)*, and of the crustal quality factor Q*(f)*. An attenuation parameter, κ_0, is also evaluated relatively to a reference rock site.

The attenuation and source parameters estimated in this study are used through the RVT in otder to predict the peak horizontal ground acceleration (PGA), and the 5% damping pseudo acceleration spectra (PSA).

INTRODUCTION

Eastern Sicily is one of the most seismically active regions in Italy. In the last 1000 years this area has experienced at least five large and destructive events (1169, 1542, 1624, 1693, 1818) with equivalent magnitude ranging from 5.5 to 7.4 (Boschi et al. 1995). The last important event (M_S = 5.3) to strike this region occurred on December 13 1990 (Amato et al., 1995), after 50 years of seismic quiescence. The epicenter was located in the Ionian sea, a few kilometers offshore from Augusta (Figure 1), on a transverse element of the Ibleo-Maltese fault system (Amato et al., 1995). In spite of being a moderate size earthquake, it damaged a wide area and produced 19 casualties, due to the collapse of a poorly constructed building in the town of Carlentini (Basili et al., 1995). The high seismic potential of the region, its population density, and the inadequacy of some of the buildings to withstand even moderate levels of ground motion make Eastern Sicily an area of high seismic risk, where modern hazard studies are needed.

The prediction of the ground shaking for engineering applications is often obtained through the use of empirical predictive relationships (Kramer, 1996), which are usually developed by regressing a large number of strong-motion data. Since there are regions with high seismic potential which do not have enough recordings of large earthquakes, it is common practice in such cases to use relationships coming from tectonically similar areas, with the assumption that the ground motions would be similar. Alternatively, we can use the predictive relationships obtained for areas in different tectonic regimes. This practice, though, could lead to unreliable estimates of the ground motions.

Boore (2001) made a quantitative comparison between the response spectra from ground motions recorded during the Chi-Chi earthquake (Taiwan, 1999) and the response spectra predicted from the four frequently used, empirical predictive models (Abrahamson and Silva, 1997; Boore at al., 1997; Campbell, 1997, 2001; Sadigh et al.,1997) that are largely based on data from California. He found that the observed motions differed from the predicted ones by factors larger than expected from earthquake-to-earthquake variations (Boore, 2001).

The same "incongruence" could be observed in Italy, where the predictive relationships for hazard maps or for estimates of the ground motions were calculated by Sabetta and Pugliese (1987, 1996) from strong motion data coming from different tectonic and geological environments (Friuli, Sicily, Irpinia and Central Italy), (Akinci et al., 2004). These equations describe the attenuation of horizontal peak ground acceleration, velocity and response spectra as a function of the epicentral distance, only in terms of constant geometrical spreading at all distances ($g(r) = 1/r$).

As suggested by Chouet et al. (1978) and demonstrated by Raoof et al. (1999) and by Malagnini et al. (2000), the linear attenuative properties of the crust at high frequencies can be evaluated using the background seismicity of the interest area. In other words, it becomes possible to develop regionally calibrated attenuation relationships even where strong motion data are not available.

Several authors have used small earthquakes, recorded in "homogeneous" tectonic regions, to define, with different methods, the crustal propagation characteristics (i.e. Aki and Chouet 1975, for Japan and California; Hermann and Malagnini 1996, for central United States; Singh et al. 1982, and Ortega et al. 2002, for Mexico; Jeon 2000, for Utah; Malagnini et al. 2002, for Northeastern Alps).

In this study we characterize the distance - scaling of the earthquake-induced ground motions in Eastern Sicily using the small earthquake background seismicity, following the approach described by Malagnini et al. (2000a). Peak ground motions of narrow band-pass filtered waveforms will be used in a general regression scheme that accounts for source excitation, crustal propagation and site effects. A subsequent modeling effort is carried out through the use of random vibration theory (RVT), (Cartwright and Longuet-Higgins, 1956), in order to obtain a simple functional form that describes the empirical excitation and the distance scaling relationships. Results of this study will be included in the most recent hazard map of Italy (Stucchi et al., 2004).

STRUCTURAL SETTING AND SEISMICITY OF EASTERN SICILY

Eastern Sicily is part of a complex structural domain that is a segment of the Alpine collisional belt developing along the Africa-Eurasia plate boundary. Three main elements mark, from north to south, the collisional complex of Sicily and its offshore continuation (Fig.1): the Sicilian compressional margin, the Gela-Catania foredeep, and the foreland area of the Hyblean-Malta

Plateau, outcropping in Eastern Sicily and in the Sicily Channel (Lentini et al., 1994, Catalano et al., 1996).

Almost all authors describe the Hyblean foreland as part of the northern margin of the African continental crust, which is bounded to the north by the thrust front of the Apennine allocthonous units, and to the east by the Malta Escarpment. It is a multiply-segmented normal faulting zone, striking NNW-SSE, dipping ENE, and developing over 300 km from North Africa to Eastern Sicily (Reuther et al., 1993; Sirovich et al., 1999). This escarpment separates the 23 km-thick continental crust of the Hyblean Plateau (Finetti, 1982) from the 13 km-thick oceanic crust in the Ionian Sea (Ferrucci et al., 1991; Reuther et al., 1993; Adam et al., 2000).

The regional tectonic stress field of eastern Sicily acts along an approximately N-S direction, and is mainly determined by Africa and Euro-Asiatic plate convergence (Bonaccorso et al., 2001). An extensional E-W trending regime is also observable along the eastern coast of Sicily, related to the Malta Escarpment (Bonaccorso et al., 2001).

Historical and instrumentally recorded seismicity is distributed mainly in two areas: moderate magnitude shallow earthquakes ($M_s \cong 5.0$) are localized in the inner sector of the Hyblean Plateau and are associated with minor structures such as the Mineo fault or the Scicli line (Fig. 1) (Azzaro et al., 2000); larger events are distributed along the Ionian coast and could be related to the activation of the Scordia-Lentini graben and the Malta Escarpment (Azzaro et al., 2000).

DATA SET

We used a data-set of waveforms from 106 earthquakes in Eastern Sicily, which were recorded by a seismic network run by the Istituto Nazionale di Geofisica e Vulcanologia (INGV, Figure 1). The 9 stations network is equipped with 24-bit digitizers, 9 MARK-L4-3D sensors, with an average sensitivity of 172 V/m/s, natural frequencies of 1,5 Hz and critical damping equal to 0.65.

Signals were recorded at a sampling rate of 125 samples/s.

Due to the heterogeneity of the surface geology in the region, the stations were deployed on different kinds of geologic outcrops. Three stations (S3R, S4R, S9R) were placed on volcanic sites (pyroclastic rocks and lavas) 50 to 100 m-thick, four stations (S5R, S6R, S7R, S8R) on 20 to 400 m-thick calcarenites. The last two stations (S1R, S2R) were put on quaternary sedimentary deposits, up to 100 m-thick. All this information about the seismic network is gathered in Table 1. We used data recorded from 04/23/94 to 10/08/01, with local magnitudes ranging from 1.0 to 4.3. We used only crustal earthquakes (shallower than 25 km). Source-receiver distances range between 10 and 130 km (Figure 2).

DATA PROCESSING

Details of the data processing scheme used in this study were described by Malagnini et al. (2000, 2002): each waveform is corrected for the instrument response, examined to eliminate those with spurious transients including double events and/or low signal to noise ratios, and is reviewed for the picking of P-wave and S-wave arrivals. We also decided to remove all the waveforms with propagation paths crossing the Etna volcanic edifice, since they had nucleated and/or traveled in a medium which strongly differs from the surrounding region. After this selection, the data-set is reduced to about 50% of its original size, and it now consists of 1311 waveforms. We rotated the horizontal recordings to radial and transverse components of the ground velocity, and applied a set of narrow band-pass filters defined around central frequencies, f_c , chosen at 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 8.0, 10.0, 12.0, 14.0 and 16.0 Hz. The band-pass filter is the combination of two 8-pole Butterworth filters: a high-pass with corner frequency at $(1/\sqrt{2})f_c$ followed by a low-pass with corner frequency at $\sqrt{2}f_c$.

On each filtered seismogram, recorded at the hypocentral distance r, we read the peak amplitude of the ground-velocity a (f_c, r). The logarithm of a (f_c, r) can be written as the summation of a source term, a site term and a propagation term:

$$\log a (f_c, r) = EXC (f_c, r_{ref}) + SITE (f_c) + D (r, r_{ref}, f_c) \qquad (1)$$

EXC (f_c, r_{ref}) is the contribution of the source to the hypocentral distance r_{ref}; this arbitrary reference hypocentral distance is chosen in between the hypocentral distance data set distribution, and large enough to avoid the effect of source depth error in the hypocentral distance. The distance of 40 km satisfies these conditions, and it is the same of similar studies in other region, so we can compare the results. SITE (f_c) is the site term. D (r, r_{ref}, f_c) is the crustal propagation term, and represents an estimate of the average crustal response for the region. For representing the distance dependence of observed motion, we approximate the attenuation term as a piece-wice linear function (Anderson and Lei, 1994; Harmsen, 1997):

$$D (r, r_{ref}, f_c) = \sum L_i(r) D_i \qquad (2)$$

where $L_i(r)$ is a linear interpolation function and D_i are node values such that D (r_i, f_c) ≡ D_i. We select the number (n) and the spacing between the nodes, based on the distribution of data with distance. The regression may fit any curvature in the actual distance dependence.

Equation (1) allows us to cast all available observations into large matrices, one for each central frequency, that are independently inverted to obtain excitation, site and propagation terms. In each regression, the degrees of freedom of the system may be reduced by forcing the propagation term to be zero at the reference distance, and by constraining a reference site term (in general, the average of a subset of site terms) to a reference (in our case, null) value. The first constraint completely decouples the propagation term from the source/site ones. The second constraint forces any systematic effect acting on the reference site(s) into the excitation terms. After identifying the station that is least affected by local effects, we decided to force only the vertical site term of this station (S6R) to be null. The horizontal components and the other station's vertical components were left free to vary during the regressions.

The constraint imposed on the vertical component of the site term implies that excitation and propagation terms are referred to the vertical motions observed at the S6R station. As observed by Atkinson (2003, 2004), we suppose horizontal S-wave ground motions to decay with distance in the same way as the vertical motions do. This assumption was thoroughly investigated in a new study by Hermann and Malagnini (2004) in which they synthesized 240 earthquakes with different focal mechanisms and crustal velocity structure. They observed that vertical ground motions depend upon focal mechanism, and, for strike-slip mechanisms, horizontal and vertical components didn't show the same behavior: in this case H/V ratios can change with distance. We took out of the regression both the horizontal components of the S7R station due to a bad signal to noise ratio. Nevertheless, the regression code would have rejected them on the ground of specific signal to noise ratio analyses. The last constraint applied on the regression is a smoothness constraint on D (r, r_{ref}, f_c) so that:

$$D_{i-1} - 2D_i + D_{i+1} = 0 \qquad (3)$$

RESULTS

Duration of ground motions

In general, duration of ground motions depends on rupture duration and on wave dispersion. Following Raoof et al. (1999), we define the duration of the ground motions recorded on each filtered seismogram, for each central frequency, as the time window bracketing the 5-75% of the seismic energy that follows the S-wave arrival. An estimate of duration of the seismic signal as a function of frequency and hypocentral distance is needed for using RVT and for obtaining a theoretical prediction for the attenuation of the peak ground velocity. The 5-75% rule is chosen after investigating the distribution of the peak values in all frequency bands. In other words, each peak value of the bandpass filtered seismograms, given the corresponding spectral amplitude and 5-75% duration, is predicted via RVT, together with a tolerance factor. With this definition of duration, most peaks were successfully predicted and lie within one tolerance factor from the observed value.

Individual duration values are regressed as a function of distance by using the same linear interpolation scheme used for regressing the amplitudes. At 1.0 Hz, duration data are severely scattered. For the other central frequencies, duration seems to be almost independent of frequency (Fig. 3).

Crustal Attenuation

Colored curves in Figure 4 show our empirical estimates for the crustal attenuation terms at the different central frequencies. These curves are plotted as the deviation from a 1/r trend (horizontal lines in the figure represent a decay ∝ 1/r) of the normalized attenuation functions.

Black lines represent theoretical predictions of the attenuation functions obtained for each central frequency through the equation:

$$D(r, r_{ref}, f) = \log g(r) - \log g(r_{ref}) - \frac{\pi f (r - r_{ref})}{\beta Q(f)} \log \mathrm{e} \quad (3)$$

Curves in Figure 4 are sensitive to the duration T, to the functional form of geometrical spreading g*(r)*, to the quality factor Q*(f)*, and to its frequency dependence. The best fit is obtained with the crustal attenuation parameter:

$$Q(f) = Q_0 \, (f/f_{ref})^{\eta} \qquad \text{with} \quad f_{ref} = 1.0,\ Q_0 = 400 \text{ and } \eta = 0.26 \quad (4)$$

and the following (continuous) geometrical spreading function:

$$g(r) = 1/r \qquad r \leq 40 \text{ km} \qquad (5)$$

$$g(r) = (1/40)(40/r)^{-0.4} \qquad r > 40 \text{ km}$$

The parameter η determines spreading of the set of curves. For $\eta = 1$, curves would lie on top of one another. The crustal attenuation parameter Q_0 trades-off with the geometrical spreading function, since both act on the steepness of the decay with distance.

Site Terms

Figure 5A shows the results of the regressions relative to the vertical site terms. Due to the constraint imposed on the site terms during the regressions, each curve is the deviation of the specific site from station S6R. There are no large deviations of the vertical site terms from S6R at various frequencies. Details on the site characteristics are shown in Table 1. A more interesting behavior is shown by the horizontal site terms, which are investigated through the use of the horizontal-to-vertical site term ratios (Figure 5B). These ratios, calculated for each station for the horizontal component resulting from the compositions of the radial and the transverse components, seem more affected by the local geology of the substratum. Unfortunately, our knowledge about the local geology of station’s sites is reduced to the info showed in Table 1. We can only suppose that the peculiar spectral ratios behavior, showed by stations S1R and S3R, could be explained with phenomena related to the less consolidated formations below them, i.e. impedance contrast and/or resonance effects.

Excitation Terms

Black diamonds in Figure 6 show the excitation terms exc(f_c, r_{ref}), obtained from the regression on peak ground velocities. They describe the vertical peak ground motion velocity, as a function of frequency, at the reference hypocentral distance of 40 km, and at the S6R station site.

We fit the empirical excitation curves with the following spectral model:

$$exc(f_c, r_{ref}) = C(2\pi f)\, M_0\, s(f)\, g(r_{ref})\, \exp[-(\pi r_{ref})/(\beta Q_0 (f/f_{ref})^{\eta})]\, \nu(f)\, \exp(-\pi f \kappa_0) \qquad (6)$$

where the rock site amplification $\nu(f)$ is fixed to 1.0. The constant C controls the low-frequency spectral amplitudes, while the stress parameter and the attenuation parameter κ_0 determine the high frequency part of the theoretical spectra. The parameters used in the constant C are the radiation pattern, $R_{\Theta\Phi}$, the partition of total shear-waves energy into horizontal components, V, and the effect of the free surface, F. These parameters were calibrated through a waveforms modeling of the largest event (the only one for which broadband waveforms were available). The earthquake was inverted using the technique by Zhu and Helmberger (1996) and results in a moment magnitude M_w 3.8.

A trade off exists between the stress parameter and κ_0, as shown in Figure 7. κ_0 governs the high-frequency decay of the theoretical excitation terms, as well as $\Delta\sigma$, which affects the radiated spectra beyond their corner frequencies. In the frequency band of our interest, however, the effect of $\Delta\sigma$ is strongest for the largest earthquakes, while κ_0 completely controls the behavior of the small earthquakes at high frequency. For these reasons, we initially search the best κ_0 in order to fit the average shape of the small magnitude events (i.e. smaller than 2.3), and then we adjust the spectral levels at larger magnitudes (Mw > 3.5) by using the appropriate $\Delta\sigma$'s . The values taken by the different parameters in equation (6) are shown in Table 2.

Di Bona et al. (1995) evaluated the source and the attenuation parameters for the 1990, Ml = 5.4, Eastern Sicily earthquake. They estimated k-values, for each station-site, ranging between 0.033 s and 0.045 s, fitting the S-wave acceleration spectra with an omega-square model (Boore, 1986). They also found a stress-drop value from 21 to 200 MPa calculated at regional and local distance, respectively. This variety of values for the stress parameter and k was attributed by the authors as due to crustal heterogeneities and near-receiver amplification due to surface geology and topography, although it could also represent the effects of unaccounted attenuation. Our estimate of κ_0 is conceptually different from the ones computed by Di Bona et al. (1995), and originally proposed by Anderson and Hough (1984), since the former is distance-independent and refers to the average network site.

The residuals from the regressions show an almost Gaussian distribution, characterized by a light degree of skewness, which is amplified by the log-log presentation (Figure 8), nevertheless, the inversions are performed using the L-1 norm. Residuals refer to data points at all frequencies. Each residual is computed by subtracting the amplitude calculated using equation (1) from the amplitude of the observed peak. Because of the presentation, the presence of outliers in any frequency band would be easily detected. For the same reason, differences in behavior for the different frequency bands would be easily detected, too.

Predicted ground motions

Using the source and the attenuation parameters estimated in this study and a set of programs called Stochastic Model SIMulation (SMSIM, Boore 1996) we predicted the expected peak horizontal ground acceleration (PGA) and the 5% damping pseudo acceleration spectra (PSA) for the eastern Sicily region.

Figure 9A shows the comparison, at moment magnitude Mw 5.0, between the attenuation relation evaluated in this study, the attenuation relation obtained regressing only strong motion data by Sabetta and Pugliese (1996) for Italy and Ambraseys et al. (1996) for the Mediterranean region and those obtained using background seismicity for the eastern Alps (Malagnini et al., 2002), for the Apennines (Malagnini et al., 2000) and for the western Alps (Morasca et al., 2003)

Comparisons are made in terms of epicentral distance, and so we transformed the hypocentral distances of our data - set using a fixed focal depth of 15 km, that is the depth of the largest earthquake recorded in the eastern Sicily (December 13 1990, Md=5.6 Augusta earthquake, PDE catalogue). Curves by Ambraseys et al. (1996) are calculated using the fault distance instead of epicentral distance. Fault and epicentral distance are nearly the same for small earthquakes, or for very large distances, but their difference could be significant at local distances, as the magnitude gets larger, due to the dimensions of the fault. This is not the case of this study, in which we work with moderate magnitude.

Eastern Sicily PGA results slightly higher respect to the other prediction. This result comes from change in attenuation of seismic waves when comparing region with different tectonic regimes. A recently deformed region, the Appenines, has strong attenuation, $Q(f) = 130 f^{0.1}$ (Malagnini et al. 2000) while attenuation is lower in western Alps, $Q(f) = 310 f^{0.2}$, due to the shallow depth of the crystalline basement and here, $Q(f) = 400 f^{0.26}$, where the seismic waves travel in the more stable crust of the Hyblean foreland.

We also compared (Fig. 9B) the acceleration response spectra for 5% damping computed using the parameters of Table 2, at magnitudes and 5.0 and frequency of 1 Hz to empirical response spectra of Sabetta and Pugliese (1996) and Ambraseys et al. (1996) and the other Italian regions.

According to new studies on the relationship existing between stress parameter and magnitude (Bodin *et al.*, 2003), the predicted amplitudes at Mw 5.0 were obtained with a slightly larger stress parameter (40 MPa).

Discussion and Conclusions

Results of this study are valid in a wide frequency range (1.0-16.0 Hz), for small magnitude (Mw ≤ 3.8) and at distances less than 70 km.

We give a quantitative evaluation of the Eastern Sicily ground motion parameters in order to decrease the uncertainties for the seismic hazard. Our results are obtained through regressions of 1311 band passed waveforms, recorded by 9 digital stations equipped with MARK-L4-3D sensors.

A crustal propagation term is obtained by modeling the empirical results with a crustal attenuation parameter Q*(f),* and a bilinear geometrical spreading defined as:

$Q(f) = 400\ (f)^{0.26}$;

$g(r) = 1/r \qquad r \leq 40$ km

$g(r) = (1/40)(40/r)^{-0.4} \qquad r > 40$ km

A trade-off exists between Q_0 and g*(r)* at short distances, while we uniquely define the parameter η (in eq. 4) that is effectively decoupled from the other attenuation parameter κ_0 (in eq. 6) by forcing the propagation term to be zero at the reference distance. Q*(f)* and g*(r)* describe the averaged attenuative characteristics of the crust in the Eastern Sicily.

There is a previous estimate of Q*(f)* available for Eastern Sicily obtained by Gianpiccolo et al. (2003), although they used a constant geometrical spreading, proportional to 1/r. There is a clear trade-off between geometric and anelastic attenuation; for this reason we do not compare our estimate of Q with the one produced by Giampiccolo et al. (2003).

By using the same approach used in this study, other authors have found different Q*(f)* relations for other Italian regions. In the Western Alps $Q(f)= 310\ (f)^{0.2}$ (Morasca et al., 2002), while in the Eastern Alps $Q(f)= 260\ (f)^{0.55}$ (Malagnini et al., 2002). Lower Q-values were found in the

Apennine and in Colfiorito area ($Q(f) = 130\ (f)^{0.1}$). These differences are linked with the different geologic and tectonic settings of the areas and they play a key rule in hazard studies.

We reproduced the seismic spectra at $r = r_{ref}$ using a Brune spectral model with a stress drop $\Delta\sigma$ = 20 MPa, a generic rock site amplification factor $\nu(f)$ = 1.0, and the high frequency cutoff parameter κ_0 = 0.01 s.

Di Bona *et al.* (1995), analyzing the 1990 Eastern Sicily earthquake for investigating source and attenuation parameters, found for κ the value of 0.040 ± 0.005 s (most of the strong motion stations were located on the Iblean platform). Based on our results, crustal wave propagation in Eastern Sicily is more efficient than in other Italian regions. The combination between the geometrical spreading function, and the parameter Q(f) is strictly related to the crustal characteristics of the Hyblean Plateau, where most of the investigated seismic rays traveled. This portion of the African foreland is essentially stable: according to seismic interpretations of Finetti (1982) it is made of about 8.8 km-thick Permo-Triassic to Tertiary carbonates and volcanic rocks underlined by 7.2 km-thick crystalline basement and 7.0 km-thick lower crust.

Finally, for investigating the horizontal site behavior we calculated the spectral ratios between the average of the horizontal components and the vertical ones for each station site (Fig. 5B). The observed H/V ratios show different behaviors for different geologic site formations.

Figure Captions

Figure 1. Structural map of the Sicily (modified from Lentini et al., 1994 and Adam et al., 2000). 1. Regional overthrusts; 2. External front of the Apennine Chain; 3. Front of the external thrust system; 4. Normal faults; 5. strike-slip faults; 6. Hyblean-Malta Plateau; 7. Gela-Catania Foredeep; 8. INGV seismic stations; 9. Scicli Line; 10. Malta Escarpment; 11. Scordia-Lentini Graben; 12. December 13, 1990 earthquake (Amato et al., 1995); 13. Epicentral distribution of the earthquakes used in this study.

Figure 2. Characteristics of our data set of seismograms recorded in Eastern Sicily. A. source-receiver distance distribution; B. distribution of recordings as a function of event depth; C. number of recordings as a function of magnitude; D. number of recordings as a function of hypocentral distance.

Figure 3. Duration of the seismic signals and associated standard errors as function of hypocentral distance for each frequency studied. A linear interpolation scheme is used in the regressions for intermediate distances.

Figure 4. Colored curves are the empirical propagation term D (r, $r_{ref,}$ f_c) at the central frequencies of 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 8.0, 10.0, 12.0, 14.0, 16.0 Hz, resulting from the regression of the peak value of the data-set waveforms. The attenuation term was forced to be zero at the reference distance r_{ref} = 40 km. Black lines represent our theoretical predictions, which were obtained, for each central frequency, through the use of RVT.

Figure 5. A. Vertical site terms obtained from the regression. Each curve describes the deviation of the specific site from the S6R station's site that was forced to be zero during the regression. B. Horizontal to vertical ratio for each site as a function of frequency.

Figure 6. Estimated excitation terms of the peak-filtered velocity at the reference distance of 40 km. Grey line are our theoretical prediction performed by using the RVT and the source

parameters in Table 2. We show only some empirical curves for a better visual inspection.

Figure 7. Trade off existing between $\Delta\sigma$ and κ_0. In the figure we show velocity spectra at two reference magnitudes (Mw 2.0 and Mw 7.0), derived by using the Brune spectral model with three different values for the stress parameter $\Delta\sigma$, and for two different values of the high-frequency attenuation parameter κ_0. Spectra are propagated to the reference distance of 40 km using the propagation characteristics of the Sicilian crust. The two values of κ_0 generically refer to rock sites (0.005 sec), and to moderately attenuating sites (0.04 sec). The three values of stress parameter are within a normal range of variability.

Figure 8. Residuals computed in the regression of peak amplitude at all frequencies.

Figure 9. Estimation of peak ground acceleration (A) and response spectra 5% damping (B) computed for M_w 5.0 earthquake at hard rock site. Results for this study, derived from the source parameters in Table 2 and the attenuation parameters obtained by fitting the empirical curves in Figure 4, are compared with attenuation relation obtained by Malagnini et al. (Apennines, 2000; Eastern Alps, 2002), Morasca et al. (Western Alps, 2003) and Sabetta and Pugliese (1996, dashed curves), and Ambraseys (1996, dotted curves). To model the absolute level of ground shaking, we estimated the stress parameter of the largest event to be $\Delta\sigma$ = 40 MPa.

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