GEOPHYSICAL RESEARCH LETTERS, VOL. 23, NO. 10, PAGES 1163-1166, MAY 15, 1996

Site and propagation effects on the spectra of an S-to-S reflected phase recorded from a set of microearthquakes in the northern Apennines (Italy)

Aldo Zollo and Giovanni Iannaccone
Dipartimento di Geofisica e Vulcanologia Università di Napoli Federico II, Napoli, Italy

Abstract. We use recordings at a single station of a shallow crustal S-to-S reflected phase generated by microearthquakes (M_L 2.5-3.5) in the Northern Apennines (Italy) to analyze source, path attenuation and site effects. A site resonance phenomenon in a narrow frequency band (6-8 Hz) has been clearly detected in the shear wave acceleration spectra, consistent with similar observations from records of microseismic noise. The non-linear inversion of acceleration spectra (which have been corrected for an average site response) yields estimates of apparent corner frequencies that are approximately constant with moment, with a mean value of 2 Hz. A significant increase with seismic moment of the spectral decay parameter at high frequencies is also observed. The anomalous moment dependence of these spectral parameters is found to be related to the existence of a cut-off high frequency limit, close to the smallest event corner frequency, which could be originated by combined site and travel path effects rather than source characteristics in the frequency range of observations (0.5-15 Hz). Independent geological, well soundings and seismic data for this site in the Apennines, suggest that the spectral shape on short-period records is mainly controlled by the damping and resonance effects of a surficial layer of alluvium Quaternary sediments (100-200m thick) characterized by low values of shear velocity and attenuation parameter.

Introduction

In this paper we analyzed eight microearthquakes for which seismograms recorded at the same stations (for several stations) showed a noticeable waveform similarity. These data were previously analyzed by *Zollo et al.*(1995) (*Z&A*) who studied a microseismic sequence that occurred on May 1987 in the Apennines, at the margin of the Po Valley, in Northern Italy. In particular *Z&A* applied a relative location technique and showed that the eight events had a close hypocenter location confined in a small volume of about 1 km^3 at an average depth of 3.5 km.

The microearthquake waveform similarity was particularly evident at a station (MIN) located at about 40 km from the epicentral area. Seismograms at MIN showed several secondary arrivals, among which *Z&A* identified a S-to-S (S̀Ś) phase reflected at about 5.0 km deep discontinuity by direct modeling of seismograms using ray-theory and complete wavefield modeling techniques (*Farra*,1990; *Bouchon*,1981; Fig.1). In the present study, we investigate the spectral characteristics of this secondary phase to determine source and attenuation path parameters. Due to the epicentral distance of the recording station, the close location and similar mechanism of the microearthquakes, the records of the S̀Ś phase at MIN for each of the events studied can be considered as a repeated seismic signal which has propagated along approximately the same ray path. This suggests the opportunity to use the redundance of information for discriminating the source from the path and site contributions.

We selected a window of approximately 5 sec centered on the S̀Ś arrival, and computed the acceleration spectrum for each event. Fig.2a shows the acceleration spectra for the various microearthquakes . The events were recorded by a three-component digital seismograph equipped with a 1 Hz Mark geophones. The spectra were instrument corrected: the frequency band selected (0.5 - 15 Hz) is within the flat region of the instrumental velocity response curve.

We note a variation in the level of the various spectra and in the high frequency spectral fall off, which is made more evident by the almost linear trend of the spectrum for frequencies higher than 3-4 Hz in the semilogarithm diagram. A peak in the spectrum can be observed around 6-7 Hz; it appears to be present, more or less pronounced, in all the spectra.

Inversion of Acceleration Spectra

To determine the parameters of source and attenuation controlling shape and level of acceleration spectra, the following formula is used to calculate the acceleration spectrum

$$A(f) = C\,\omega^2\,M_o\,S(f, f_c)\,e^{-\pi T^* f} \qquad (1)$$

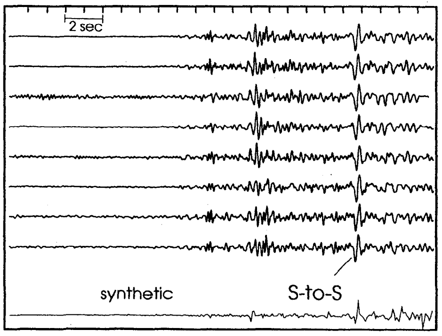

Figure 1. Seismograms of the EW component recorded at station in Minerbio village (MIN) for the analyzed events. The bottom trace is the synthetic computed by using the complete wavefield modeling (*Bouchon*, 1981).

Paper number 96GL00971
0094-8534/96/96GL-00971$05.00

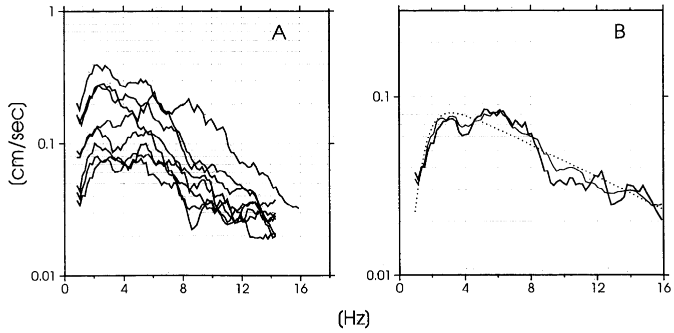

Figure 2. a) Acceleration spectra of the S̀Ś wave selected for the eight microearthquakes. b) Example of spectral misfit. The figure shows the observed spectrum (thick line) and those calculated by applying (thin line) or not (dotted line) the convolution for site response.

where M_o is the seismic moment, f the frequency and f_c the corner frequency of the spectrum. The constant C contains the terms of Green's function (geometrical spreading, radiation pattern and reflection/transmission coefficient for the S̀Ś).

The shape of the S-wave source spectrum is assumed according to the model proposed by *Boatwright* (1978)

$$S(f, f_c) = (1 + (f/f_c)^{2\gamma})^{-1/2} \qquad (2)$$

where the exponent γ is a source parameter, which controls the high frequency spectral fall off of the seismic radiation. In equation (1), the exponent accounts for the effect of the path anelastic attenuation, where $T^* = \frac{T}{Q}$. T is the travel time of the considered S̀Ś phase and Q is the shear-wave quality factor, which was assumed independent on frequency in the frequency band of analysis.

The estimation of the model parameters from the spectral amplitudes data was carried out by using a non-linear inversion technique which is based on the search for the minimum of a *cost* function $\Phi(\mathbf{p}) = \sum_i w_i (A_i^{obs} - A_i^{cal})^2$, which defines the goodness of misfit between data and observations for a given model parameter vector $\mathbf{p}$ ($\mathbf{p} \equiv (M_o, f_c, \gamma, T^*)$). A_i^{obs} and A_i^{cal} are the values of the acceleration amplitude spectrum observed and calculated, respectively, for each frequency f_i employing equation (1).The sum is computed over the frequency in the selected range. $w_i = 1/N_i$ is a weighting coefficient for the i-th spectral coordinate, and it is defined as the inverse of the value of the noise spectrum N(f) measured at the frequency i. To calculate N(f), we selected a time window preceding the S̀Ś arrival on the seismograms.

The search for the minimum of the misfit function $\Phi(\mathbf{p})$ is based on the SIMPLEX technique, which requires estimate of the function itself rather than of its derivatives (*Press et al.*, 1986). Due to the trade-off between the parameters γ and T^* (both controlling the high frequency spectral fall off), we chose at first to fix the parameter γ=2 and γ=3 (corresponding to ω-square and ω-cube models), in accordance with the seismic source models usually employed to interpret the radiation spectra observed (e.g., *Aki*, 1967; *Brune*, 1970; *Hanks*, 1979).

We obtain a less consistent match between the observed and theoretical data using γ=3, which is also confirmed by the relatively higher values of the misfit function. Therefore a value of γ=2 was chosen for the analysis.

We calculated the ratios between the observed and computed spectra for the best-fit models. Fig.3a shows the average spectral ratio and the limits $\pm 1\sigma$. The spectral ratios clearly show a peak at 5-8 Hz, introducing a spectral amplification of about a factor 1.5- 1.8 at such frequencies with respect to the values predicted by the model (1). Fig.3b shows the noise spectra relative to a window on the seismogram preceding the first P arrival, for the three recordings for which this signal was available. These noise spectra also show a significant peak at a frequency of about 6 Hz, which supports the hypothesis of a resonance effect generated in the proximity of the recording site.

The average spectral ratio in Fig.3a, was assumed to be a representative site response function, and subsequently used to correct the acceleration spectra for the site effect. The source and attenuation parameters were then computed again by inversion of the corrected acceleration spectra. When acceleration spectra are corrected for site response, we observe a ~60 % of variance decrease with respect to inversions made using uncorrected spectra (fig.2b).

The inversion of acceleration spectra corrected by the average site response provides estimates of spectral parameters f_c, $\Omega_o$and T* for each of the considered events. Seismic moments estimates are inferred from the low-frequency spectral level Ω_o.

Plots of f_c vs M_o and T* vs M_o are shown in Fig.4. This figure shows that estimates of spectral corner frequencies are roughly constant around a value of 2 Hz for seismic moments ranging over about one order of magnitude and that. Furthermore the attenuation parameter T* varies significantly with M_o, with larger T* values associated with higher seismic moments. In figure 4 the notation *apparent* for f_c and T* indicates that these quantity are considered *apparent* estimates of the *true* values which are actually unknown.

Numerical tests showed that fixing T* at a known value, spectral amplitudes could be equivalently well fitted by an adequate value of γ (in the range 1 to 3). In this case an increase of γ with M_o has been observed, which means that T* and γ trade-off and cannot be estimated independently from the actual data set.

Discussion and Conclusion

If the corner frequency - seismic moment scaling law in Fig.4a is controlled by source properties, the derived stress drop increases with moment by about one order

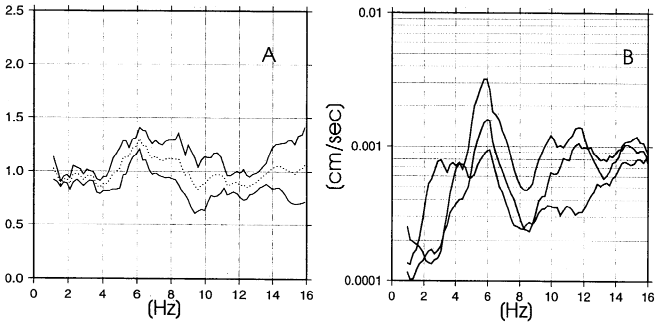

Figure 3. a) Average spectral ratio between observed and computed spectra (dotted line). Solid lines represent $\pm 1\sigma$ error interval. b) Spectra of noise computed for a 5-sec window preceeding the first P-arrival.

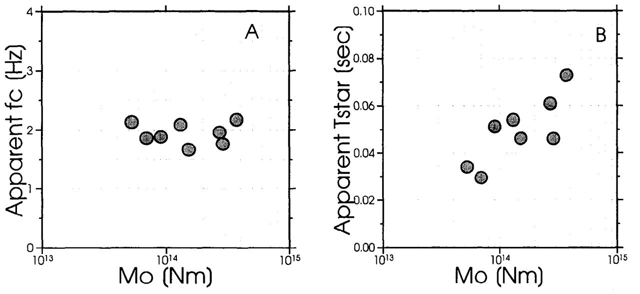

Figure 4. a) Plot of retrieved *apparent* corner frequency (f_c) vs seismic moment (M_o). b) Plot of retrieved *apparent* T* vs seismic moment.

of magnitude over the observed moment range. Nevertheless, we note that the estimated corner frequencies of our microearthquake data set are significantly smaller than values currently observed for events of similar magnitude (M_L 2.5-3.5) recorded in tectonic and volcanic provinces (e.g., *Hanks*, 1977 and references in; *Lindley and Archuleta*, 1992).

In addition, geological and well soundings data for the site of MIN show the presence of a 150-200m thick shallow layer of alluvium sediments characterized by rather low shear velocity values (about 300-400 $m \cdot s^{-1}$) (*Z&A*, *AGIP*, unpublished data) . No measurements of Q for the shallow clay layers are available in the area, but the evidence for extremely low S-wave velocities and laboratory and geotechnical measurements for similar geological contexts in the Apennines suggests an important attenuation effect of surficial rocks on seismic motion in the range 1 - 20 Hz (*Mancuso et al.*, 1995). Furthermore, simple calculations made by assuming near-vertical plane wave propagation through the alluvium layer indicate resonance frequencies higher than 0.5-1 Hz; the sharp decrease in the S-wave velocity in the very shallow sedimentary layers is therefore expected to cause important amplification of seismic motion in the observed frequency range.

We suggest that the observed dependence with moment of both the high frequency fall off and corner frequency parameters could be due to the combined effect of a narrow band site amplification and travel path attenuation effects.

Anderson and Hough(1984)(*A&H*), based on the analysis of acceleration spectra from different magnitude earthquakes, proposed a model for describing the high frequency behaviour of spectral acceleration $A(f) = const \cdot e^{-\pi \mathcal{K} f}$ (for $f > f_E$), where $\mathcal{K}(r) = \mathcal{K}_o + \alpha r$ is an attenuation parameter and r is the hypocentral distance. $\mathcal{K}_o$ is a site attenuation parameter, while α accounts for the travel path attenuation. f_E is a cut-off frequency, higher than the corner frequency, which was experimentally determined by *A&H* in the range 3-5 Hz and represented a suitable frequency above which the acceleration spectral decay is attributed only to the attenuation effect.

Note that the attenuation filter used for spectral inversion (equation 1) is equivalent to that proposed by *A&H*. Since our observations concern a single station and the same source receiver distance, local site and whole path attenuation cannot be discriminated by actual data.

The inversion results shown in Figure 4 therefore indicate that an additional effect to attenuation must control the shape of the spectrum at frequencies close to the observed apparent corner frequencies and cause the apparent moment dependence of fall off parameter.

In order to check how the results are sensitive to the attenuation model assumed for the inversion, we used a band-limited attenuation filter of the form:

$$\begin{array}{ll} e^{-\pi T^*(f-f_H)} & \text{for } f \geq f_H \\ 1 & \text{for } f < f_H \end{array} \qquad (3)$$

and the source spectrum of equation (2) for generating synthetic spectra in the same range used for data inversion (0.5-15 Hz). The function (3) simulates an attenuation effect which is dominant only at frequencies higher than a cut-off limit f_H. We assume f_H physically represents an additional corner frequency in the acceleration spectrum, beyond which the spectral behaviour changes drastically and is mainly controlled by site/path attenuation effects.

Different values of f_H and T* were considered for the tests. A number of synthetic spectra were generated with corner frequencies in the range 2 - 10 Hz and seismic moments scaled according to a constant stress drop model ($\Delta\sigma = 5$ MPa). The inversion of synthetic spectra thus obtained was performed by using the Simplex method and the spectral model of equation (1).

Results of these simulations are shown in Figure 5 for values of $f_H = 2$ Hz and T*= 0.24 sec. The retrieved corner frequencies are approximately constant with moment, with a mean value close to f_H, while T* appears to increase with moment, as an effect of using a band-limited frequency range for the spectral inversion. The anomalous moment dependence of *apparent* f_c and T* can be therefore related to the existence of a cut-off frequency f_H close to the minimum corner frequency considered. Assuming the attenuation mechanism of equation (3), values of $f_H \sim 2$ Hz and T* ~0.2-0.25 sec are able to produce the observed dependence of corner frequencies and spectral decay parameter T* with seismic moment.

The inversion results and numerical simulations for the studied data set show the need to introduce an additional cut-off frequency in the acceleration spectral model for explaining observations in a band-limited frequency range. In our modeling this frequency, denoted as f_H, has the same meaning of the high frequency limit $f_{\max}$ widely observed on strong motion and short period records of different magnitude earthquakes (*Hanks*,1982; *Aki*, 1988). The origin of $f_{\max}$ is still debated and it is attributed either to source or

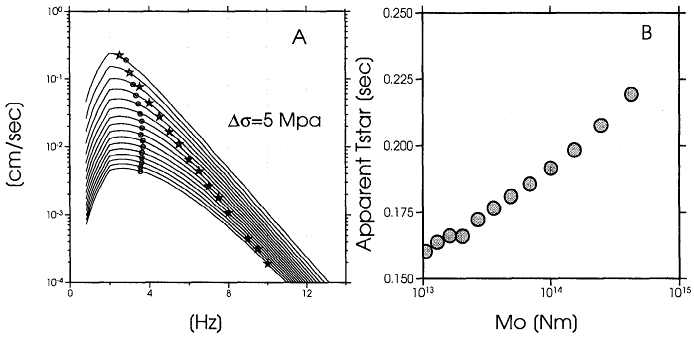

Figure 5. a) Theoretical acceleration spectra computed using the source model of eq.2 and the attenuation filter of eq.3. Circles and stars are the retrieved (apparent) and *true* corner frequencies, respectively. b) Plot of the retrieved (apparent) T* values vs seismic moment.

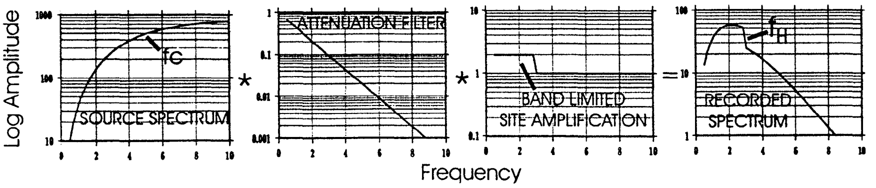

Figure 6. Qualitative sketch for describing the change of the acceleration spectral shape induced by a coupled effect of attenuation and band-limited site amplification. The asterisk denotes convolution. A limited band amplification at low frequencies, due to site resonance phenomena, can originate a cut-off frequency f_H.

path attenuation effects (e.g., *Hanks,* 1982; *Anderson,* 1986; *Aki,* 1988; *Gariel and Campillo,* 1989). In figure 6 is proposed a qualitative explaination for the origin of this high frequency limit, as due to the coupled effect at low frequencies of attenuation and site amplification. A spectral cut-off frequency can result from a band-limited amplification of frequencies smaller than 1-3 Hz (related to the resonance of near surface low velocity sediments), which arises in addition to the exponential decrease of the spectral amplitudes due to the dominant effect of attenuation at higher frequencies. However, due to the cut-off of spectral amplitudes produced by the short period instrument response, our data set cannot clearly resolve differential amplification effects on spectra for frequencies smaller than 1-2 Hz. Unfortunely, no high quality direct P and/or S wave records are available for the analyzed site to check independently these results. Our conclusions therefore assume similar spectral shape for direct and reflected shear waves travelling from the source to the recording site. According to results from this study and independent geological, well soundings and active seismic data, we conclude that the seismic spectral shape in the 1-15 Hz in this region of Apennines can be strongly contaminated by the damping and resonance effects of the alluvium Quaternary sediments (100-200m thick), characterized by low values of shear velocity and attenuation parameter.

Acknowledgements. We thank P. Bernard, G.De Natale and J.Virieux for enlightening discussions and suggestions during the preparation of this work. Comments and criticisms from Jack Boatwright and an anonymous reviewer helped to improve the clarity of the paper. This work is sponsored by AGIP and Gruppo Nazionale Difesa dai Terremoti.

References

Aki, K., Scaling law of seismic spectrum, *J. Geophys. Res.*, 72, 1217-1231,1967.

Aki, K., Physical theory of earthquakes, in *Seismic Hazard in Mediterranean Regions*, eds J.Bonnin et al., Kluwer Ac.Pub., 1-33, 1988.

Anderson, J.G., S.E. Hough, A model for the shape of the Fourier amplitude spectrum of acceleration at high frequencies, *Bull. Seism. Soc. Am.*, **74**, 1969–1994, 1984.

Anderson, J.G., Implication of attenuation for studies of earthquake source, in *Earthquake Source Mechanics*, Das et al. Eds, Am.Geophys.Union, Washington D.C:, 1986

Boatwright, J., Detailed spectral analysis of two small New York State earthquakes, *Bull. Seism. Soc. Am.*, **68**, 1117–1131, 1978.

Bouchon,M.,A simple method to calculate Green's functions for elastic layered media, *Bull.Seism.Soc.Am.*, **71**, 959-971, 1981.

Brune, J.N., Tectonic stress and the spectra of seismic shear waves from earthquakes. *J. Geophys. Res.*, **75**, 4997–5009, 1970.

Farra,V., Amplitude computation in heterogeneous media by ray perturbation theory: a finite element approach, *Geophys.J.Int.*,**103** ,341-354,1990.

Gariel, J.-C., Campillo, M., The influence of the source on the high-frequency behavior of the near-field acceleration spectrum: a numerical study. *Geophys. Res. Let.*, **16**, 279-282, 1989.

Hanks, T.C., Earthquake stress-drops, ambient tectonic stresses, and stresses that drives plates, *Pure Appl. Geophys. Res.*, **115**, 441-458, 1977.

Hanks, T.C., b values and ω^γ seismic source models: implications for tectonic stress variation along crustal active fault zones and the estimation of high frequency strong ground motion, *J. Geophys. Res.*, **84**, 2235-2242, 1979.

Hanks, T.C., $f_{\max}$,*Bull.Seism.Soc.Am.*, **72**, 1867-1880, 1982.

Lindley G.T., Archuleta R.,J., Earthquake source parameters and the frequency dependence of attenuation at Coalinga, Mammouth Lakes, and the Santa Cruz Mountains, California. *J. Geophys. Res.*, **97**, 14137-14154, 1992.

Mancuso C., Silvestri F., Vinale, F., Italian experiences on dynamic in-situ and laboratory measurements of soil properties, Proc. III National Earthquake Engineering Conference, Istanbul, 1995.

Press, W.H., Flannery, B.P., Teukolsky, S.A., and W.T. Vetterling, *Numerical recipes*, Cambridge Un. Press, Cambridge, 1986.

Zollo, A., De Matteis R., Capuano P., Ferulano F., Iannaccone G., Constraints on the shallow crustal model of the Northern Apennines (Italy) from the analysis of microearthquake seismic records, *Geophys.J.Int.*,**120**, 646-662, 1995.

A. Zollo and G.Iannaccone, Dip. Geofisica e
Vulcanologia, Lgo. S.Marcellino, 10 80138 Napoli,Italy
(e-mail: aldo@dec.dgv.unina.it)

(received April 3, 1995; revised August 8, 1995;
accepted February 3, 1996.)