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Modelling of ground acceleration in the near source range: the case of 1976, Friuli earthquake ($M = 6.5$), northern Italy

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Abstract

A mixed statistical-deterministic model of earthquake rupture is developed for evaluating the strong ground motion in the near source range (receiver distance comparable to the fault length). The source parametrization is based on the k-square model and the propagation is computed by asymptotic Green's functions. The method is applied to the case of 1976, Friuli earthquake ($M = 6.5$) in northern Italy which occurred on a low-dip thrusting fault. Acceleration records at 29 stations are computed for 100 simulations of rupture histories. The mean value map of peak ground accelerations shows clearly a maximum to the south due to the inner geometry and directivity of the source. The variation of the estimated PGA versus the epicentral distance is strongly dependent on azimuth and is not decreasing monotonically. The comparison of these curves with those predicted by empirical acceleration–distance relationships shows discrepancies in the near source distance range. This study shows the importance of considering the complexity of the source rupture process for strong motion estimate in the near source range.

Introduction

The prediction of strong motion parameters (peak acceleration/velocity, amplitude and frequency content of response spectra) of moderate to large earthquakes provides a quantitative characterization of seismic hazard in an active seismic area. The methods for estimating the seismic hazard are generally based on a statistical description of seismicity and use empirical relations between magnitude (or epicentral intensity) of earthquakes and expected peak ground acceleration as a function of the distance from the fault. Most of these relations account only for average characteristics of the earthquake rupture process and seismic wave propagation. They are generally verified at large distances from the source region although in some applications recent updated databases can be used also to predict strong motion at close distances (Abrahamson and Shedlock, 1997; Boore et al., 1997). At distances which are comparable to the fault dimension, the effect of rupture complexity and directivity increases the variability of ground motion high frequency records ($f > 1$ Hz).

Recently, several authors have proposed numerical methods for simulating the wave field radiated during the rupture process along extended faults (Cotton and Campillo, 1995; Gariel and Campillo, 1989; Beroza and Spudich, 1988; Fäh and Suhadolc, 1994), by including in the modelling, the effects of source and propagation complexity.

Recent studies of crustal events have shown that heterogeneous patterns of final slip distribution and rupture velocity on the fault plane as inferred from the inversion of accelerograms, teleseismic and geodetic data are rather complex at high frequencies (Hartzell and Heaton, 1983; Heaton, 1990). The complexity of the rupture nucleation, propagation and healing process is related to the variable rock strength and/or yielding stress along the faulting zone and can result from the irregular and segmented geometry at small scale of the fault surface. Moreover, observations of rock fracture at different scales suggest that the faulting process does not repeat the same styles of nucleation, propagation and arrest during successive faulting episodes which occur along a given fault zone.

On the other hand, the evidence for periodic recurrence of rupture events along the same fault (or fault system) suggests that the geometry, mechanism and average slip per event could be constant at the scale of thousands of years, these parameters being mainly related to direction and intensity of the large scale tectonic stress regime. These ideas are supported by the numerous paleoseismic studies of Quaternary active faults in different tectonic environments (e.g. Pantosti and Valensise, 1990).

In this paper, we applied a mixed statistical-deterministic approach for evaluating the strong ground motion parameters for the 1976, Friuli mainshock in northern Italy. This moderate size event ($M = 6.5$) occurred along a low-angle dipping thrust fault in the region of the northeastern Alps.

The method is based on the extensive computation of synthetic accelerograms produced by a large number of possible rupture models along a fault whose dimensions, orientation and mechanism are assumed to be known. Different rupture processes are simulated by assuming a statistical distribution of kinematic parameters which control the nucleation, the propagation of the rupture and the space-time history of slip during the rupture process. We adopted a kinematic description of the source and applied the self-similar k^2 model proposed by Herrero and Bernard (1994) to determine the final slip amplitude distribution on the fault.

The ray theory allows for very fast computation of synthetics in a high frequency range. Nevertheless complete wave field methods can be applied, provided that the regional and local structure details are adequately known at the wavelengths of interest.

In the case of Friuli, at regional scale, several 2D models have been proposed based on large distance refraction profiles (Slejko et al., 1987). At local scale, few near-surface structure studies are available (i.e. Giorgetti and Stefanini, 1989). However, the available models for the 3D Friuli local and regional structure are not sufficiently detailed at the short wavelengths scale corresponding to the considered high frequency range (1–20 Hz). Since our study is mainly focused on investigating the effect of source rather than path complexity on near source strong motion records, we assumed a homogeneous model for propagation and computed the direct S-wave field which can be considered dominant in amplitude in the selected distance/frequency range.

The range of expected maximum variation for peak ground acceleration and spectral ordinates are estimated as functions of distance and azimuth from the fault in the near source range, in the frequency band 1–20 Hz.

Method

Far-field modelling of strong motion

Acceleration records close to the earthquake faults show that the complexity of the rupture process dominates the seismic radiation at short distances from the fault (distances smaller than some fault characteristic lengths) and for frequencies higher than 1 Hz. At these distances and frequencies, the body waves, which are emitted by the rupture during the faulting process, dominate largely in amplitude with respect to secondary and surface waves when site effects are weak. On the other hand, following Bernard and Madariaga (1984) and Farra et al. (1986), the asymptotic solution of wave equation represents a good approximation for the near-source wave-field when the observed wavelengths are shorter than the minimum distance of receiver from the radiating source. Thus, we applied a method to simulate the ground acceleration at the Earth surface radiated from an extended fault which is based on the far-field approximation of the wave field (Aki and Richards, 1980):

$$\ddot{\mathbf{u}}_{\mathrm{c}}(\mathbf{x},t) = \frac{\partial^2}{\partial t^2}\int\int_{\Sigma} G_{\mathrm{c}}^{FF}(\mathbf{x},\mathbf{y};t,0) * \Delta\dot{u}(\mathbf{y},t-T_{\mathrm{c}})\,d\Sigma, \qquad (1)$$

where $\ddot{\mathbf{u}}_{\mathrm{c}}(\mathbf{x},t)$ is the simulated ground acceleration corresponding to the wave phase c, $\mathbf{x}$ and $\mathbf{y}$ represent respectively the coordinates of the receiver and the fault points, $G_{\mathrm{c}}^{\mathrm{FF}}$ is the asymptotic Green's function, $\Delta\dot{u}$ is the slip velocity function, T_{c} is the travel time and Σ is the fault surface.

Following Farra et al. (1986), the Green's function of a direct body wave in a layered elastic medium can be expressed as:

$$G_{\mathrm{c}}^{\mathrm{FF}} = \frac{\mu_{\mathrm{o}}}{4\pi\rho_{\mathrm{o}}c_{\mathrm{o}}^3}\mathrm{Re}\left\{\sqrt{\frac{\rho_{\mathrm{o}}c_{\mathrm{o}}}{\rho\;c\;J}}F_{\mathrm{c}}\,\Pi\right\}\delta(t-T_c), \qquad (2)$$

where μ_o, ρ_o, c_o are respectively the shear modulus, density and wave velocity evaluated at the source, J is the geometrical spreading factor, F_c is the double-couple radiation pattern coefficient and Π contains the product of all complex wave transmission coefficients at the different interfaces of the layered medium. Each of Green's function computed by (2) is convolved in the frequency domain by the Azimi's attenuation function, parametrized by a constant quality factor Q_c (Aki and Richards, 1980), which accounts for the anelastic effect of the Earth.

The slip velocity function is approximated by a box-car function:

$$\dot{u}(\mathbf{y}, t) = \begin{cases} \frac{D(\mathbf{y})}{\tau(\mathbf{y})} & \text{for } t_r(\mathbf{y}) < t < t_r(\mathbf{y}) + \tau(\mathbf{y}) \\ 0 & \text{for } t < t_r(\mathbf{y}) \text{ and } t > t_r(\mathbf{y}) + \tau(\mathbf{y}), \end{cases} \quad (3)$$

where D is the final slip, t_r is the rupture time and τ is the rise time. Both D, t_r and τ are assumed to be dependent on the fault coordinate $\mathbf{y}$.

The fault surface is represented by a rectangular plane which is discretized in subfaults and the integral in (1) is solved numerically by a summation over all the subfaults.

For a given fault geometry and a given mechanism, the Green's function relative to a given subfault-receiver travel path is computed at the beginning and stored in a table for each of considered receivers. This table is used for computing synthetic accelerograms for different simulations of the rupture process along the given fault plane.

The rupture model

To account for the observed complex final slip distribution during earthquakes, we considered in our modelling that at each fault point (subfault) a different value of final slip can occur. According to the work of Andrews (1981) and to the recent studies of Bernard (1987), Frankel (1991) and Herrero and Bernard (1994), ω-square acceleration spectra at high frequencies can be related to a self-similar distribution of slip and stress-drop on the fault plane following a negative power-law of radial wavenumber k, under a constant rupture velocity assumption.

In our simulations, we adopted the k-square model proposed by Herrero and Bernard (1994). The distribution of the final slip parameter on the fault is computed by applying an inverse 2D Fourier transform to the complex function:

$$\widetilde{\Delta u}(k_x, k_y) = \left|\widetilde{\Delta u}(k_x, k_y)\right| \exp\left(i\,\Phi(k_x, k_y)\right), \quad (4)$$

where the amplitude spectrum in (4) is approximated by Herrero and Bernard (1994) by

$$\left|\widetilde{\Delta u}(k)\right| = \text{const}\,\frac{1}{1 + (k/k_c)^2}, \quad (5)$$

where $k = \sqrt{k_x^2 + k_y^2}$, and choosing a random phase function Φ for radial wavenumbers $k > k_c$. The wavenumber limit k_c is taken as that corresponding to the minimum fault dimension (Herrero and Bernard, 1994). To avoid the sharp slip transitions at the fault edges the slip distribution is smoothed using a 2D cosine-taper filter. The constant in (5) is finally evaluated by normalizing the slip distribution so as to make the total seismic moment on the fault equal to a given value.

In this study, we assume a constant rupture velocity, i.e. circular rupture fronts, and a random position on the fault for the rupture nucleation point. As a first order approximation, we consider, following the k-square model, that the slip heterogeneities produce a dominant effect on the far-field seismic radiation with respect to the irregularities in the rupture front shape (i.e. constant rupture velocity). This may be not a valid approximation for highly discontinous fracture phenomena, characterized by sharp accelerations/decelerations of the rupture front. Nevertheless, it is a reasonable assumption when the rupture velocity is smoothly variable along the fault surface.

We also assumed τ uniform on the fault and equal to the cut-off low-pass filter applied on synthetic records. This is equivalent to assuming a delta-like slip velocity function in (1), which physically corresponds to an instantaneous rise of slip at the rupture front passage. Due to the low-pass filtering effect introduced by a finite value of rise time on synthetics, the assumption of a negligible value of τ in our modelling corresponds to maximizing the expected amplitude of wave motion in the far-field.

In order to avoid the numerical effects of discretization on synthetics (e.g. aliasing), a fine fault gridding (characteristic subfault dimension of 20–30 meters) is needed for simulating accelerograms at frequencies up to 20 Hz. We performed a number of preliminary tests using decreasing subfault dimensions and various rupture velocities and receiver distances. These tests showed that, for subfaults lengths smaller than 20–30 meters and a maximum frequency of 20 Hz, the shape of the far field velocity pulse is not sensitive to the details of the slip velocity at the individual subfault, while its amplitude is controlled by the factor $\frac{D}{\tau}$, which depends on the subfault position. We therefore used in our modelling an approximated slip velocity function:

$$\Delta\dot{u}(\mathbf{y},t) \approx \frac{D(\mathbf{y})}{\tau(\mathbf{y})} f(t),$$

where $f(t)$ is a trapezoidal function with duration $\tau + \frac{\Delta l}{v_r}$ (Δl is the smallest subfault dimension and v_r the rupture velocity) (Bobbio, 1995; Emolo, 1997).

The 1976, Friuli earthquake ($M_L = 6.5$)

Tectonic setting and seismicity

The region of Friuli is located in the eastern sector of the Southern Alps. The orogenesis of the Southern Alps is related to the convergence of European and Adriatic plates, started in the Upper Cretacic (about 70 million years ago). The studies of seismicity and neotectonic movements indicate that such a convergence process is still active. At regional scale, there are two main tectonic structural features: the southern Alps and the Dynaric system. Geological and geophysical investigations show that these structures are composed of a series of south-verging nappes which pile up through EW and SE–NW-striking overthrusts (Barbano et al., 1985) (Figure 1).

A subsystem of strike-slip faults oriented NS, intersects the thrust fault system. Fault geometry and movements related to these structures are consistent with the present regional stress regime which shows a maximum compressive stress mostly oriented NNW–SSE.

The May 6, 1976 Friuli earthquake ($M_L = 6.5$) struck the region after a seismic quiescence period of several centuries. It was preceded by a $M_L = 4.5$ precursor, and followed by numerous aftershocks till September 1977, the largest of which occurred on September 15, 1976 ($M_L = 5.8$ and $M_L = 6.1$). The historical catalogue shows that earthquake swarms, with similar magnitude, occurred in 1348 and 1511.

The mainshock has been located about 25 km North of the town of Udine, at a depth of about 10 km (Barbano et al., 1985). The focal mechanism has been determined by teleseismic data (Cipar, 1980) and is consistent with geodetic measurements (Briole et al., 1986) (Figure 1). It shows a thrust fault solution with the two conjugate planes oriented EW (266°) and dipping respectively 78° and 12° to the North. Geodetic and geological data indicate that the rupture plane is the lower dipping one (Briole et al., 1986).

Table 1.

Length (L)	13 km
Width (W)	13.8 km
Strike	270°
Dip	12°
Slip	90°
Maximum depth	12.9 km
Minimum depth	10 km
Rupture velocity (v_R)	3 km/s
Rise time (τ)	0.05 s
Seismic moment (M_0)	2.9 10^{25}dyne cm
Average final slip $< \Delta u >$	54 cm

Fault parameters and velocity model used for simulation

Several authors have studied the 1976 Friuli earthquake by interpreting the teleseismic records (Lyon-Caen, 1980; Cipar, 1980; Barbano et al., 1985), acceleration records (De Natale et al., 1987), geodetic measurements (Briole et al., 1986), aftershock locations and mechanisms (Slejko and Renner, 1982; Briole et al., 1986).

The fault parameters used in our study are listed in Table 1. The fault dimensions, mechanism and seismic moment are constrained by teleseismic and geodetic measurements. The rupture plane is chosen according to results of modelling of leveling data (Briole et al., 1986). The fault depth is somewhat uncertain, being poorly constrained by teleseismic and long period data (Cipar, 1980; Lyon-Caen, 1980). We chose a maximum depth of almost 13 km which is consistent with teleseismic estimates and the depth of early aftershocks (Briole et al., 1986).

In this study, we considered only the direct S-wave field contribution. Infact, several numerical tests showed that, in the investigated range of distances (smaller than 40 km) and frequencies (higher than 1 Hz), the direct S waves largely dominate in amplitude direct P and converted/reflected waves in a layered structure. The Green's functions of direct S-waves are computed by asymptotic ray approximation of the wave field in a homogeneous ($V_S = 3.5$ km/s) half-space. The anelastic attenuation was taken into account by convolution of synthetic records with the Azimi's function, with a constant Q_S parameter. An average crustal Q_S value of 300 indipendent of frequency has been assumed in our simulations based on the recent attenuation study of Castro et al. (1996), who analyzed both micro-earthquakes and strong motion records.

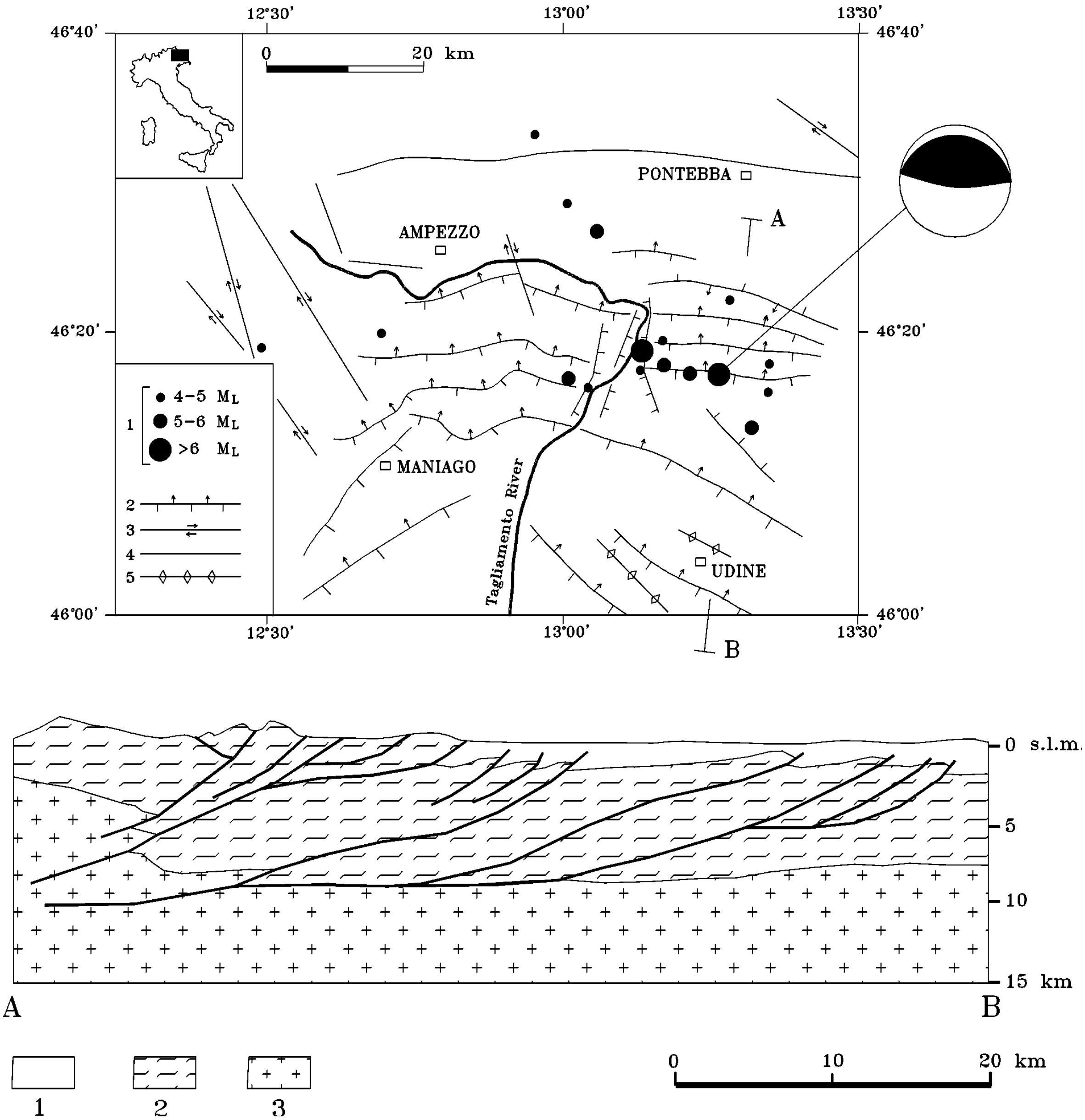

Figure 1. In the upper part are shown the main neotectonic structural features for the Friuli region; also is shown the focal mechanism of the May 6, 1976 earthquake. 1: epicenters; 2: dip-slip faults (arrows according to the dip direction); 3: strike-slip faults; 4: faults with undetermined character; 5: anticline axis. In the lower part is shown an attempt at seismotectonic interpretation for the cross section AB with the estimated fault-plane dip of the events reported in the upper part of the figure. 1: Quaternary and Cenozoic; 2: Mesozoic and Paleozoic with Alpine orogenesis; 3: Paleozoic with hercynian and Alpine orogenesis and metamorphic basement. (Modified from Barbano et al., 1985).

The average final slip value was obtained by seismic moment and fault surface. The slip direction is assumed uniform along the fault plane and consistent with the long period focal mechanism solution. The fault plane was discretized using square subfaults with dimension 0.025 × 0.025 km^2. The rupture time of each subfault was computed according to a constant rupture velocity of 3 km/s. The slip duration (τ) is also assumed constant on the fault and equal to 0.05 s, which corresponds to the short period limit of our simulations.

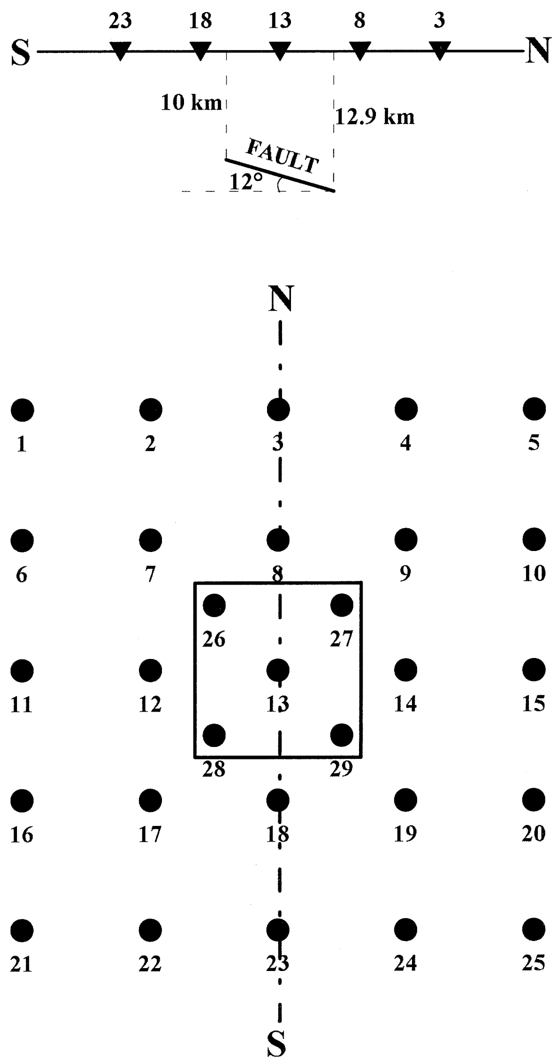

Figure 2. Bottom: station location used for the simulations with respect to the fault spatial position. Top: cross section along a north–south profile passing through the fault.

Results: Estimates of strong motion parameters

Figure 2 shows the fault and receiver configuration assumed for our simulation analysis. The 29 stations are located on a grid which covers an area of 40 × 40 km^2 including the fault surface. The spacing between adjacent stations is 10 km.

A number of 100 simulations was performed by using different slip distributions on the fault according to the k-square model and randomly varying the position of the rupture nucleation point on the fault. Figure 3 shows examples of slip distributions computed by assuming a k-square model . The synthetic accelerograms were computed at the 29 stations for each simulation of the slip distribution.

Spatial variation of Peak Ground Acceleration

The mean values and the standard deviations σ of ground accelerations are inferred from synthetic horizontal records at each station. The map of PGA shown in Figure 4a represents the expected spatial variation of the mean value of peak acceleration for possible simulated rupture processes on the fault associated to the Friuli earthquake. Mean peak values of 0.5 g are expected at distances from the fault smaller than 15 km, for a $M{\approx}6.5$ thrusting event having characteristics similar to those of the Friuli earthquake. The map shows that the PGA are maximum South of the fault. This spatial variation is mainly controlled by the peculiar effect of source geometry and directivity related to the low-dip fault angle to the north. Infact, ray take-off angles from the fault normal of S-waves emitted by fault points during the rupture propagation, are, on average, larger for stations located south of the fault. This is the cause for a strong ground motion amplification at distances comparable with the fault size, which becomes dominant relative to the amplitude decrease due to geometrical spreading and attenuation.

Figure 4b is a map of the coefficient of variation (C.O.V. (%) $= 100\frac{\sigma\langle \mathrm{PGA}\rangle}{\langle \mathrm{PGA}\rangle}$). This quantity expresses the normalized range of variation for PGA at a given station due to the variable complexity of the rupture process. The expected range of variability for PGA exceeds 50% only in areas where smaller PGA values are observed. In the central area the PGA C.O.V. are smaller than 50%.

To study the variability of peak acceleration versus distance in the near source range, we select the synthetic records along various azimuths from the epicenter and plot the simulated peak values (Figure 5). For near-source distances and low-dip fault, as for the Friuli case, the decay of peak acceleration with distance is mainly controlled by the source geometry and directivity effects. An increase of peak acceleration with distance is expected in the south direction due to the peculiar fault geometry and dip. In the same figures are reported the attenuation laws obtained by regression of data by Faccioli (1979) and Sabetta and Pugliese (1987). Both of these empirical curves are extrapolated from large distances records and no azimuthal variation is taken into account due to the poor coverage of the source. In particular Sabetta and Pugliese's curves

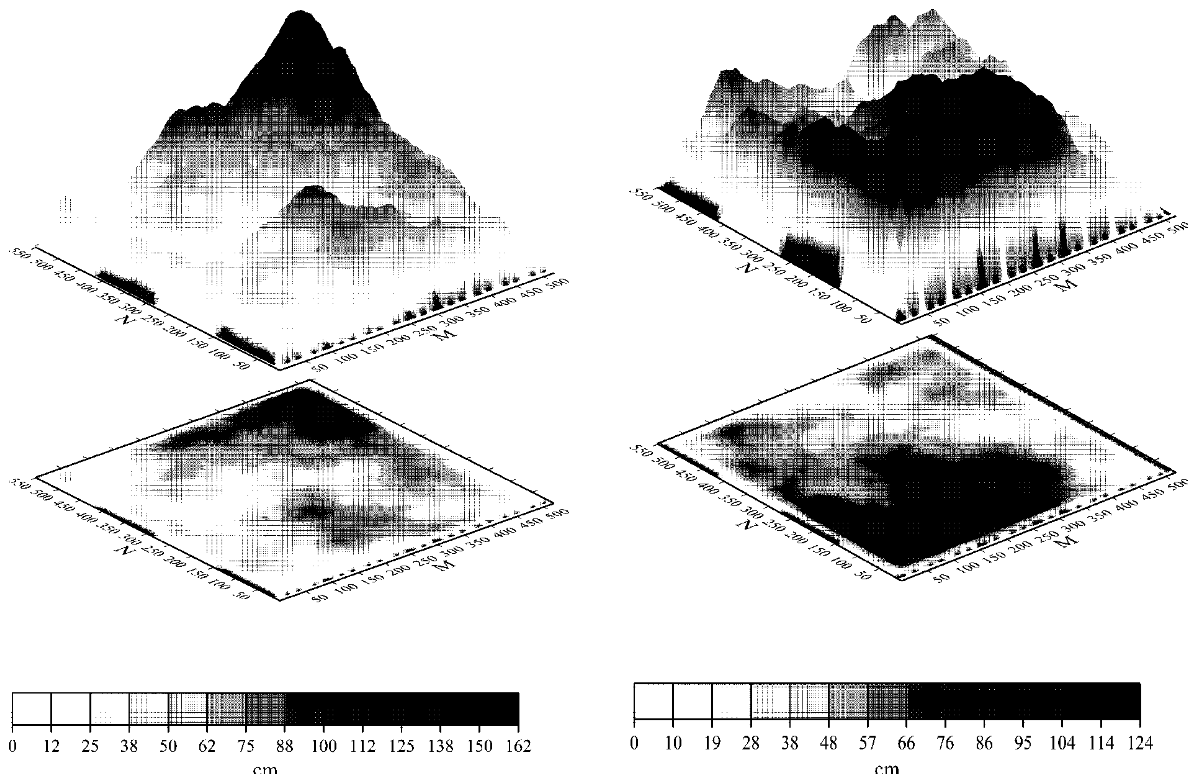

Figure 3. Some examples of final slip functions used for the simulations. For each simulation, the final slip distribution is represented both in a 3D perspective and in a grey shaded projection on the fault plane.

(1987) represent average estimates based on different earthquakes with variable fault geometry, orientation and mechanism. The comparison with synthetic curves shows that this extrapolation is not adequate to predict strong motion at the near-source distances south of the fault.

On the other hand, we note that the curves given by Faccioli (1979) and Sabetta and Pugliese (1987) are a good average when compared with the results from our modelling over all profile angles.

Waveform character and spectral shapes of synthetics

The frequency content of synthetic signals was analyzed by computing Fourier spectra (Figure 6). Generally, the acceleration spectra show the typical ω-square behaviour at frequencies higher than the corner frequency. The sharp amplitude decay at frequencies larger than 20 Hz is an effect of the low pass filtering. At a given station, the high frequency level and the bandwidth of the radiated spectra for different slip models and nucleation points are controlled by the corner frequency, as shown in the example of Figure 6. According to the ω-square model, high frequency spectral levels scales with the squared ratio of corner frequencies $\left(\frac{A_1}{A_2} = \frac{\omega_{1,c}^2}{\omega_{2,c}^2}\right)$.

The corner frequency is related to the duration of dominant S-waves, which is mainly governed by rupture directivity. Due to the peculiar fault geometry and dip, the duration, amplitude and frequency content of radiated signals thus appear strongly dependent on the relative positions between the rupture nucleation point on the fault and the station (Figure 7).

In Figure 8 we compare the spectrum of the south component of the observed acceleration record at station Forgaria-Cornino with synthetics for the south component obtained for different rupture models at a station located at similar epicentral distance and azimuth. We do not aim at reproducing exactly the observed waveforms, but only look at similarity in the global shape and frequency content of the synthetic with observed strong motion, and verify that the observed spectrum stands in the range of the expected spectra of our simulations.

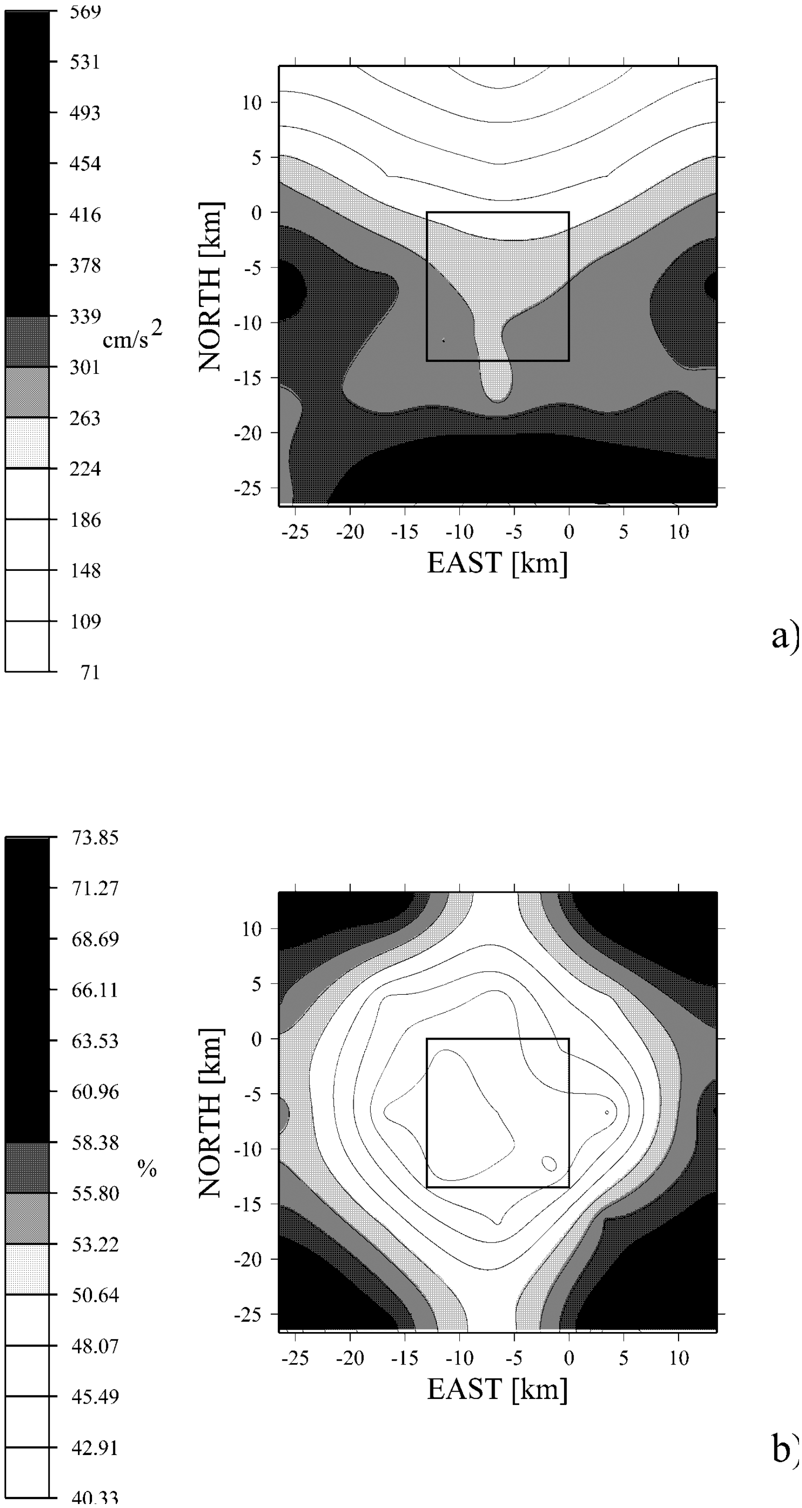

Figure 4. (a) Simulated acceleration field (mean values on 100 simulations). (b) Map of coefficient of variation. The black square in the pictures represents the surface projection of the fault.

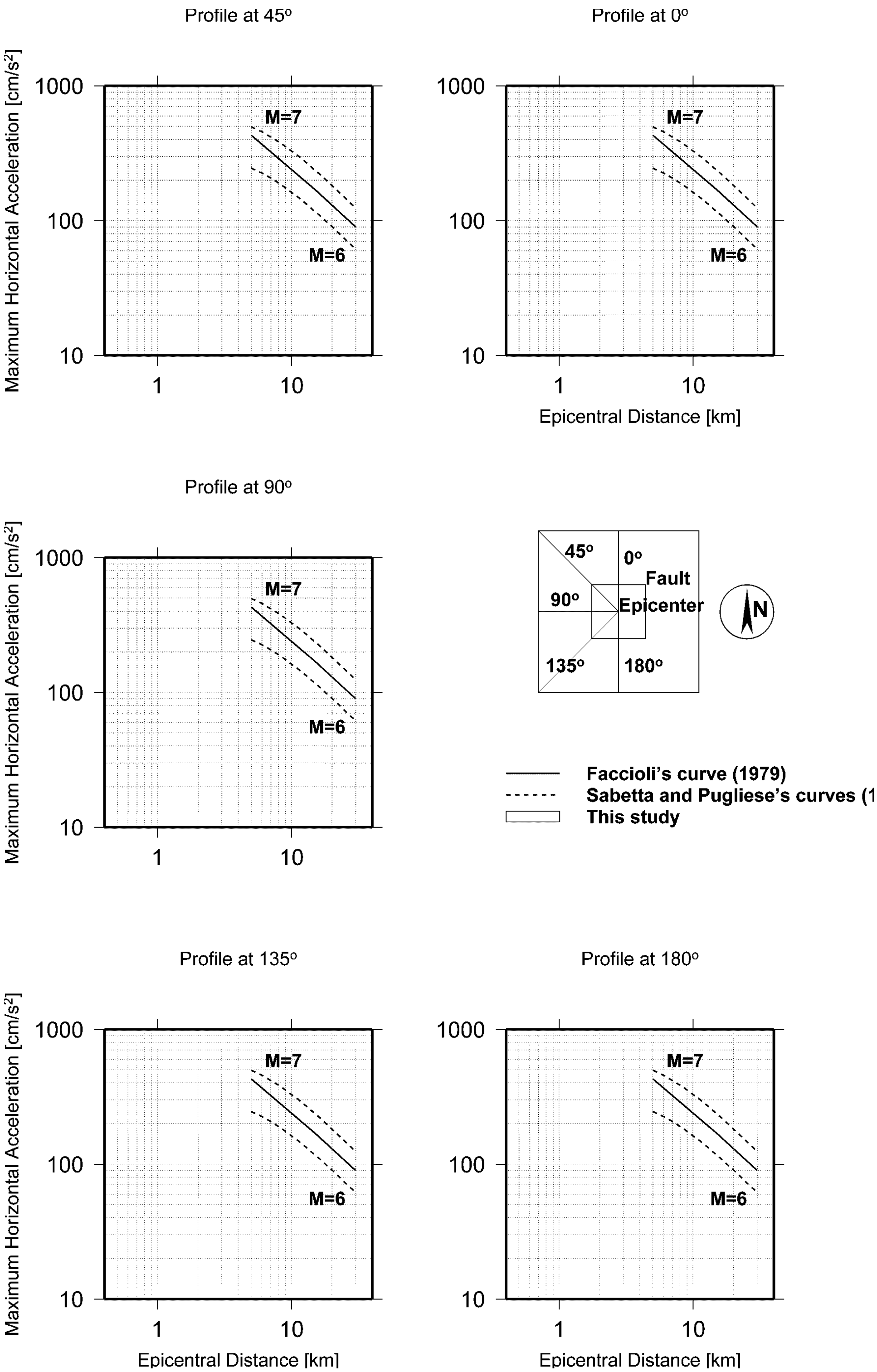

Figure 5. Maximum horizontal simulated acceleration (mean values and standard deviations) versus epicentral distance for various profiles. Each frame represents the calculated PGA along a given azimuth. The shaded zone corresponds to the (mean-σ, mean+σ) zone of our study. Moreover are reported on each frame the curves established by Faccioli (1979) (continuous line) and Sabetta and Pugliese (1987) (dashed line) for $M = 6$ and $M = 7$.

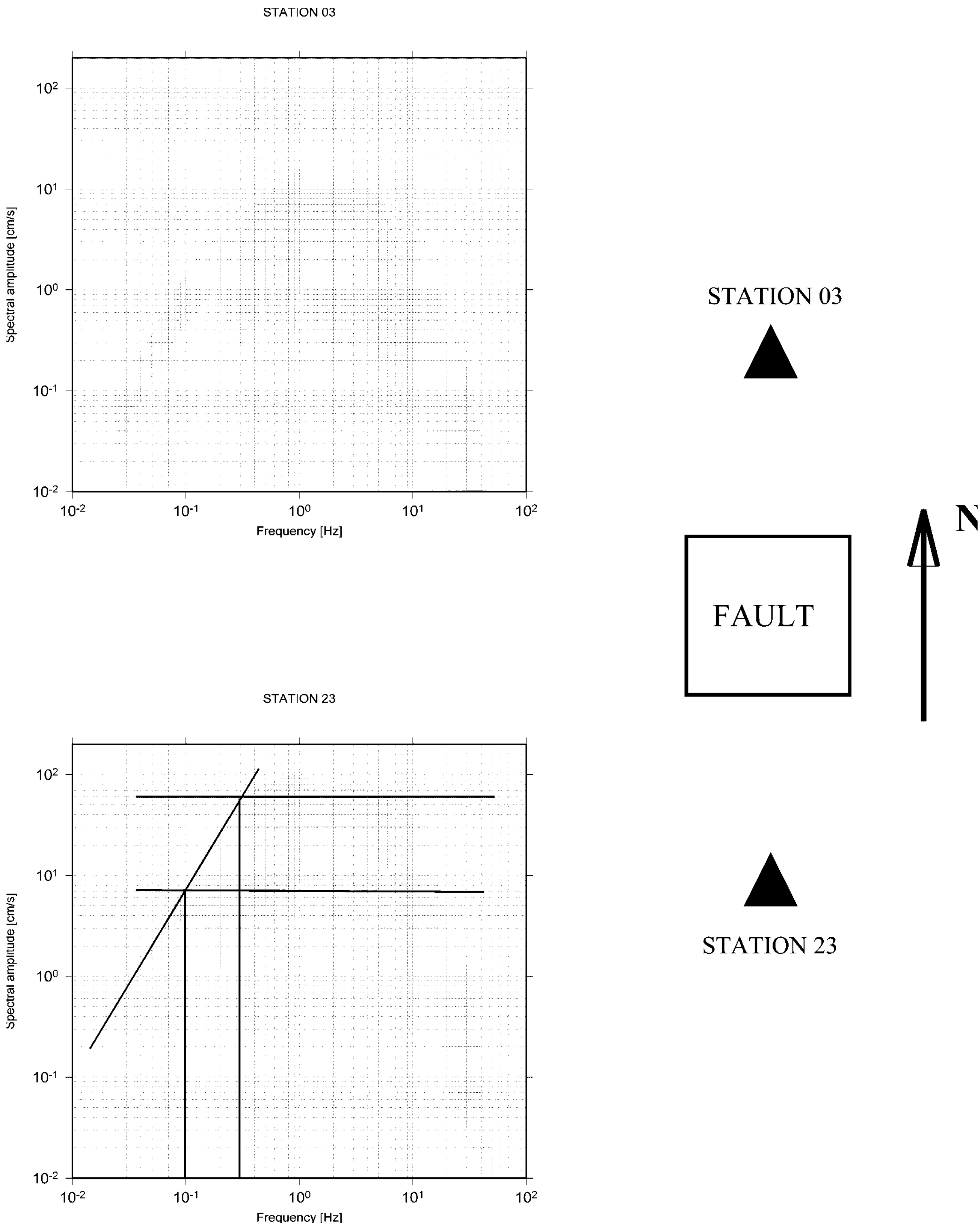

Figure 6. Fourier spectra of south component of records corresponding to 25 different simulations for station 03 (north of the fault) and for station 23 (south).

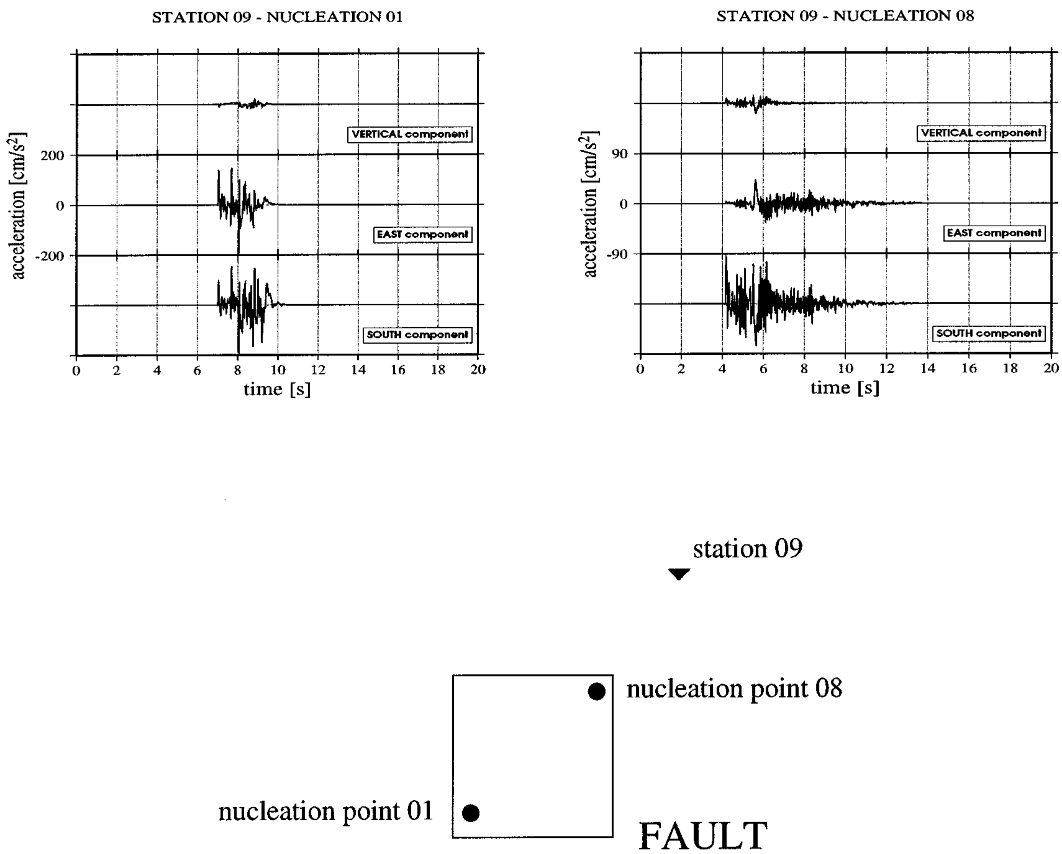

Figure 7. Effect of directivity on the synthetic seismograms duration and amplitude.

These acceleration spectra show comparable high frequency levels and similar bandwidth. The observed spectrum is more peaked around 2–5 Hz, while synthetics show a rather uniform amplitude in the range 1–10 Hz of maximum spectral energy. Discrepancies between observed and synthetic records can be attributed to the inadequate modelling of near surface site effects, which have been observed for accelerometric stations recording the Friuli earthquake sequence (Basili et al., 1981; Scherer, 1985).

As a first order approximation, the site effect can be modeled by 1D plane wave propagation in a layered structure which describes the sharp decrease of S-wave velocity and attenuation parameter in the very shallow layers near the recording site (Murphy et al., 1971). In order to quantify the effect of near site structure on the acceleration records, we estimated the response of a multi-layered structure to a near vertical incident SH plane wave by using the Thomson-Haskell method. The velocity model was obtained by cross-hole measurements in the Friuli area and is considered as reference model for sub-surface soil structures in the region (Table 2). Synthetic records which include the site effect were computed by convolution of the asymptotic Green's functions and the impulse response of a layered sub-surface structure. Examples of site corrected records for a north-south profile are shown in Figure 9.

Table 2. 1D velocity model for a sedimentary rock site in the Friuli region from cross-hole data at Tolmezzo and S.Rocco accelerometric stations (Faccioli, personal communication)

Depth	v_p [km/s]	v_s [km/s]	Density [g/cm^3]	Q_S
0–15	2.25	0.85	2.3	100
15–60	3.75	1.65	2.3	100
>60	6.0	3.46	2.6	300

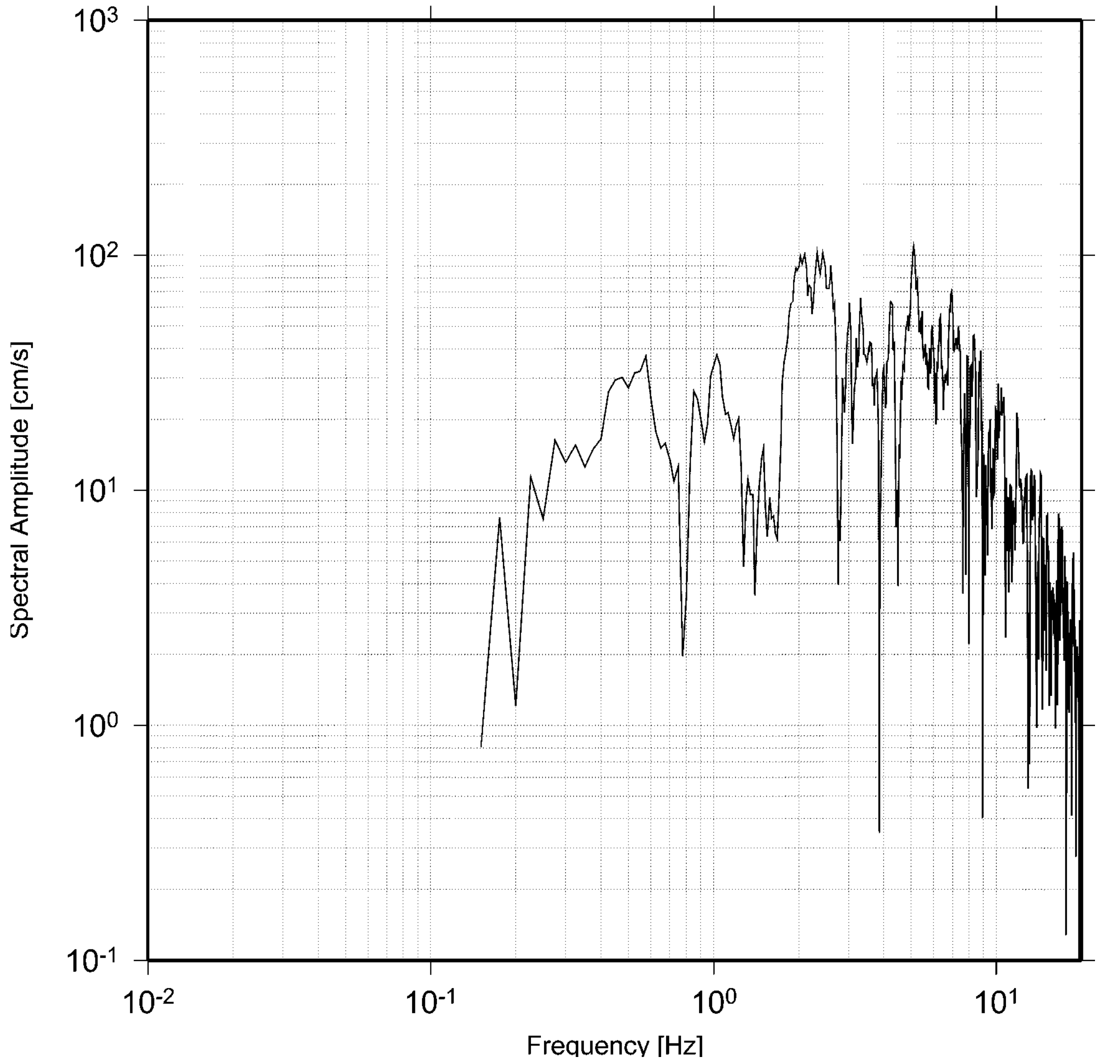

Figure 8. 25 simulated Fourier spectra area (in grey) compared with the Fourier spectrum recorded at Forgaria Cornino for the May 15, 1976 aftershock. The south component of ground motion records is plotted.

Discussion and Conclusions

In this paper, we applied a mixed statistical-deterministic approach to simulate the strong ground motion produced by a moderate size earthquake rupturing the shallow crust along a low-dip thrust fault. The source geometry and mechanism closely represent the faulting event which stroke the Friuli region in 1976, producing vast damage and casualties. The interest to study such a peculiar source geometry relies on the anomalous pattern of peak accelerations expected at the Earth surface for faulting along low angle fracture surfaces in the upper crust.

The method is based on the massive computation of synthetic strong motion records for a large number of rupture histories, each of them characterized by a different distribution of final slip at the fault and nucleation origin. Slip distributions were computed applying the k-square model proposed by Herrero and Bernard (1994). The S-wave field recorded at a simulated network of accelerographs was computed using the asymptotic approximation of Green's functions and the anelastic attenuation of the Earth is accounted for by a constant Q operator.

The use of ray theory allows for very fast computation of synthetics in a high frequency range ($f > 1$ Hz). Nevertheless, 1D/3D complete wave field methods can

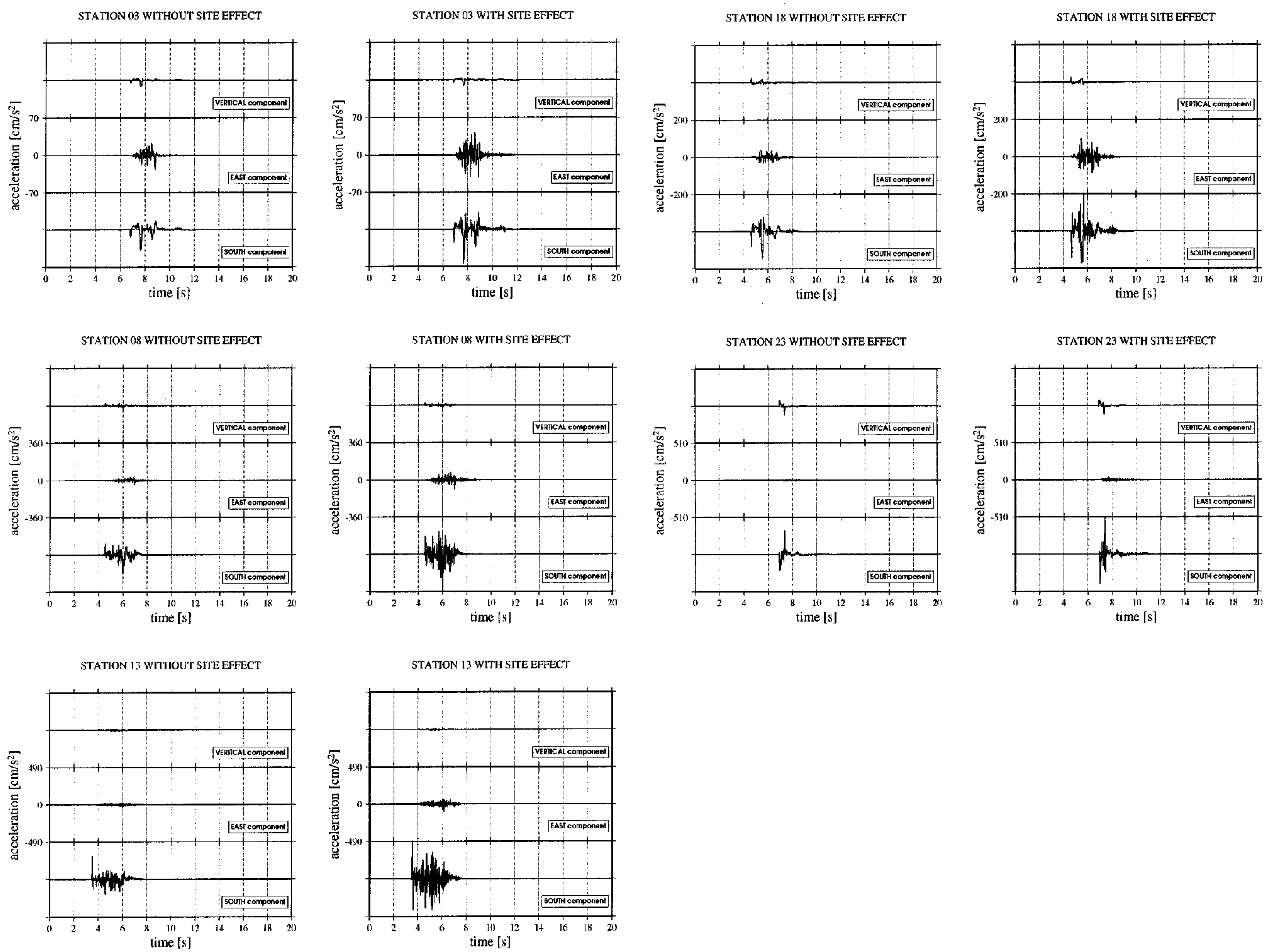

Figure 9. Examples of synthetic seismograms without and with site effect along a North–South profile.

be applied for computing Green's functions in (1), provided that the regional and local structure details are adequately known at the wavelengths of interest. Obviously the computation of high frequency complete wave field synthetics is heavly time consuming and limits seriously the explored range of source parameters.

The present study is mainly focused on investigating the effect of source rather than path complexity on near source strong motion records. In the considered case the available models for the 3D Friuli local and regional structure are not sufficiently detailed and accurate in the wavelengths (hundreds meters – 2 km) and frequencies (1–20 Hz) ranges of strong motion simulations. For these reasons we assumed a homogeneous model for propagation and computed the direct S-wave field, which is dominant in the cosidered distance/frequency range.

In the modelling of strong motion radiation associated to the Friuli earthquake we described the source complexity as mainly due to the variation of the nucleation point and spatial heterogeneous distribution of slip on the fault. We assumed that parameters such as source mechanism, geometry and location of the fault and total seismic moment are rather well constrained by long period teleseismic and geodetic observations.

A number of 100 simulations at 29 different stations were performed to retrieve the statistical properties of strong motion parameters (peak values, time duration, response spectra and frequency bandwidth). Our simulations show that both source directivity and source geometry can be the dominant factors which control the amplitude and duration of the high frequency S-wave motion in the near source range of a low-angle thrust fault. For distances smaller than 40–50 km from a 10×10 km^2 fault, the attenuation curves of peak ground acceleration are extremely variable with azimuth and can occasionally show an increase of the parameter specially along direction where the maximum variability of radiation pattern is expected.

The comparison of observed records for the Friuli earthquake and synthetics computed for several rupture histories shows that the spectral shapes and signal durations are satisfactorily reproduced by our modelling.

Several studies have pointed out the evidence for important site resonance and attenuation effects which contaminated the Friuli records, related to the subsurface lithology, low Q and shear velocities (Basili, 1981; Scherer, 1985). As a first order approximation, we included in our modelling the site response by computing the impulse response of a layered attenuating structure, using the Thomson-Haskel matrix method for wave propagation.

Strong motion records of earthquakes generally show horizontal components which largely dominate relative to the vertical ones. We considered the only SH impulse response in order to maximize the effects on amplitudes of horizontal ground motion. Due to the large variability of the expected and observed site effects in the Friuli region, this approximated modelling of site and source is not meant to provide quantitative matching of observed records.

Generally, PGA with site effect are a factor 1.5–2 higher than the ones without site effect, assuming characteristic 1D model for sedimentary rock site in Friuli. These amplifications are expected in the frequency range 1–10 Hz.

This work emphasizes the importance of source rupture process complexity to estimate the acceleration field due to an event in the near source range.

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