NUMERICAL SIMULATION OF THE REFERENCE GROUND MOTION IN FABRIANO (MARCHE, ITALY)

Enrico PRIOLO[1]

SUMMARY

The reference ground motion due to an earthquake in Fabriano (Marche, Italy) is estimated with a deterministic approach. The ground motion is computed by the «Wavenumber Integration Method», a 3-D method which solves the full equation of seismic wave propagation through a layered medium. The scenario earthquake is April 24, 1741, *M = 6.2* «Fabrianese» event, and simulates the maximum expected event close to the town. In the first part of this study, the effect due to changes of the epicentral distance and hypocentral depth is evaluated. In this case, the earthquake is represented by a point source. In the second part, a rupture propagating along an extended fault is simulated. The ground motion is computed at different epicentral distances, though at the same source-receiver azimuth.

The main results of this study consist of a data set of seismograms, Fourier and response spectra, and estimates of the peak ground motion. It is shown that the ground motion depends strongly on both the source parameterisation (depth and focal mechanism) and the source-receiver geometry (distance and azimuth). For instance, a deeper source has the effect of moving the zone of peak ground motion far from the epicentral area. Response spectra are consistent with those computed independently by a different approach, such as those estimated from empirical attenuation laws and probabilistic methods. Simulations predict no relevant effect of the rupture directivity on the ground response in Fabriano. This fact follows probably from the particular position of the town with respect to the fault plane, i.e., sideways to the fault on the hanging wall.

INTRODUCTION

Following the September 1997 earthquake sequence which struck Italy in the border area between the Umbria and Marche regions, the National Civil Protection started a seismic microzonation pilot project. The coordination of the activity was entrusted to the *National Group for the Defence Against Earthquakes (CNR-GNDT)* and the *National Seismic Service (SSN).* The study concentrated on an area which encompassed three towns, namely Fabriano (AN), Nocera Umbra (PG) and Sellano (PG); the aim was to create a reference framework for the mid- and long-term planning for the reconstruction [12]. One of the sub-tasks of the Project was the evaluation of the reference seismic motion, a task that had to be carried out through the use of different methodologies. This paper reports the activity carried out for Fabriano by one of the groups participating in the Project. Following a deterministic approach, the aim was to build up a data set of synthetic seismograms and response spectra to be used, in particular, by engineers dealing with the study and design of structures.

The scenario earthquake is the 24 April, 1741, *M* = 6.2 «Fabrianese» earthquake [13], an event close and strong enough to induce heavy damage in the town (Fig. 1). Choosing a historical earthquake also comes from the absence of earthquake instrumental records useful for this kind of study. The event is located at about 8 km NE from Fabriano [13]. A normal fault mechanism with NW-SE oriented strike was chosen, this is a typical

[1] *Osservatorio Geofisico Sperimentale, Trieste, Italy Email: epriolo@ogs.trieste.it*

mechanism of the Northern Apennines area [9, 11, 20], and similar also to the main shocks of the September 1997 sequence [2].
The synthetic seismograms are computed by the Wavenumber Integration Method (WIM) [10]. The method solves the 3-D full elastic wave equation in a plane layer medium. WIM synthetic seismograms are highly realistic for the assumed structure and fault mechanism, since all phases are correctly reproduced, in both the near- and the far-fields. These properties make this method suitable for the purpose of this study, where any analysis of local response due to lateral inhomogeneities is deliberately omitted.
This study is divided into two parts. In the first part, the effect of varying the source position on the ground motion, i. e. epicentral distance and hypocentral depth, is evaluated. This part is carried out using a point source model, which is useful for evaluating the upper and lower bounds, and the spatial variability of the ground motion for several source definitions. In the second part, a rupture along a finite fault segment is simulated. This source model is certainly more realistic for an intermediate sized earthquake such as the one of this study. The nucleation at different points on the fault segment has been simulated. In both cases, the ground motion has been computed not only for Fabriano, but also for several epicentral distances along the direction connecting Fabriano to the epicentre of the event of April 24, 1741 (NE-SW direction).

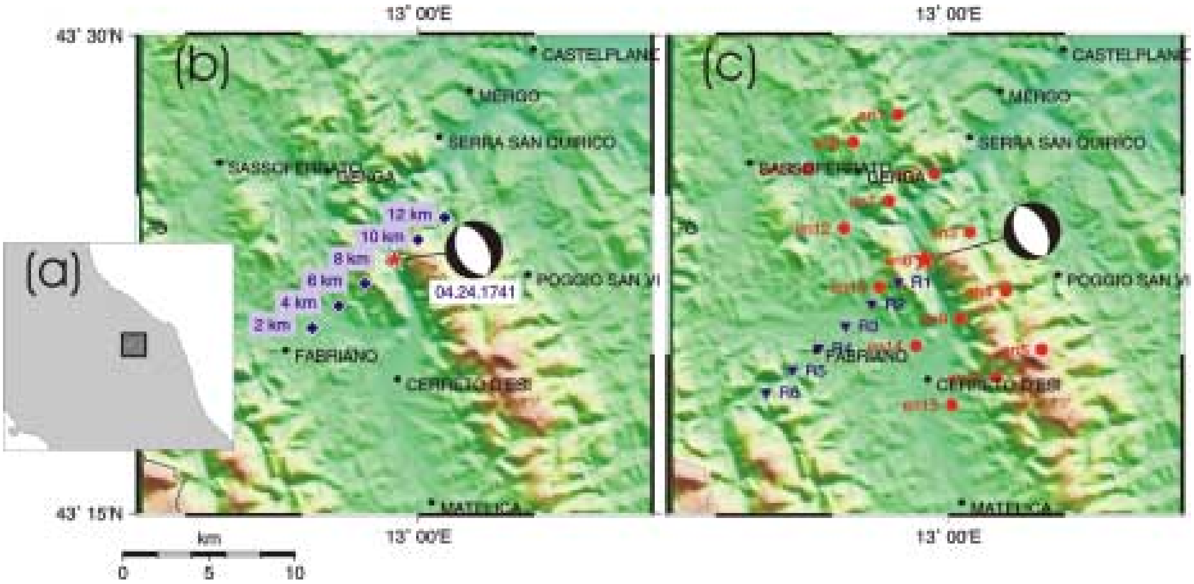

Figure 1. General maps. (a) Location of the study area in Central Italy. (b) General setting of the experiment performed with the point sources. Blue diamonds indicate the group of epicentres located at increasing distance from Fabriano. (c) The same, but for the extended source. Red circles and upside-down blue triangles indicate the epicentre of the elementary sources and the receivers, respectively.

SOURCE AND MODEL PARAMETERIZATION

The crustal model is taken from the average model of Italy developed by Costa *et al.* [7], i.e. the part representing the Umbria-Marche region. It consists of 14 layers defined in terms of P- and S-wave velocity, density and attenuation (Fig. 2). The main acoustic impedance contrasts are located at depths of about 2 and 30 km. In the uppermost 300 m, the average value of the shear wave velocity is V_S = 1400 m/s.
Central-Northern Apennines are characterised by the coexistence of both extensional and compressive structures [11, 20], all more or less NW-SE oriented. The first ones line up along the Apenninic chain, while the second ones lie along its N-NE margin. The epicentre of the April 24, 1741, M = 6.2 «Fabrianese» earthquake – hereafter called reference epicentre - has been located on the basis of historical studies at (43.383N, 12.983E) [13], right at the transition of the two regions [18]. Most authors agree on assigning this event to the extensional area [4, 20]. This study assumes a pure normal mechanism defined by $(\varphi, \delta, \lambda) \equiv (150°, 40°, -90°)$, where φ, δ, and λ are fault strike, dip, and rake, respectively, which is also similar to that of the main shocks of the September 26, 1997, Colfiorito sequence [2, 4, 9]. However, the mechanism could be completely different, e. g. transcurrent, as suggested by some authors [6] for other historical earthquakes occurring in nearby areas.
The fault segment size is estimated to be of about 20×10 km^2 [19]. The hypocentral depth has been set similar to that of the Colfiorito events, that is $z_S \cong 6$ km [2], but it might be much deeper [5, 8], even of some tens of kilometres [14]. Assuming a stress-drop value of 130 bar, characteristic for the extensional mechanism in Apennines [17], the seismic moment results equal to $M_0 = 3.1 \times 10^{25}$ dyna $\times$ cm. This value is consistent with the

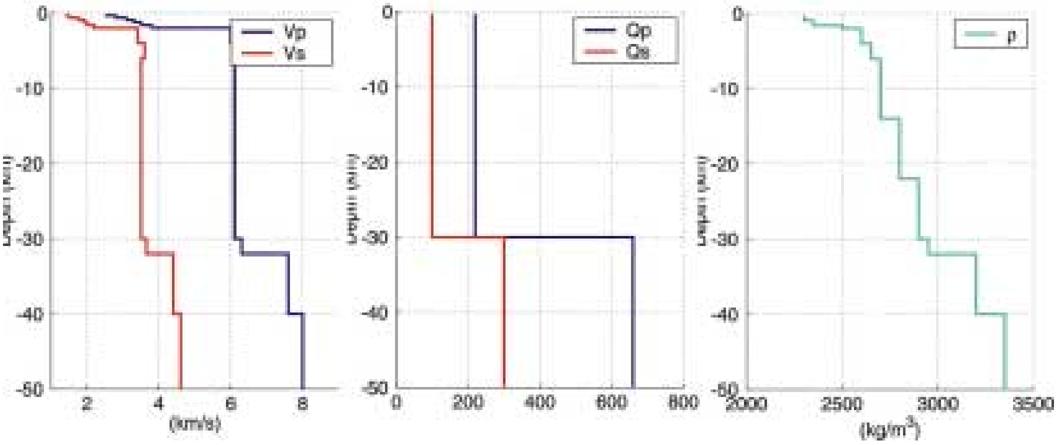

Figure 2. Plane layer model used to define the crustal structure of the Umbria-Marche area [7]. Vertical

value $M_0 = 1.1 \times 10^{25}$ dyna $\times$ cm estimated by Westaway [20] for the same event, but using a magnitude $M = 6.0$, on the base of former catalogues. According to the ISTAT catalogue of Italian municipalities, Fabriano coordinates are (43.335N, 12.905E). The distance and azimuth from the reference epicentre are respectively 8.24 km and 228°N.

ANALYSES WITH A POINT SOURCE

The purpose of the simulations performed with a point source is to analyse the effect of a change in the depth and distance of the source from Fabriano. The use of this source model reduces the computational time and thus makes it possible to evaluate several hypotheses. The results presented hereafter should be analysed by a cross-comparison, while if taken alone are less meaningful. In fact, for an $M = 6.2$ earthquake and receivers in the range of 10 km from the epicentre, the point source model generates synthetic seismograms which are unrealistically impulsive, and therefore characterised by a higher peak value and shorter duration.

In this group of experiments, six epicentres are aligned along the direction connecting the reference epicentre to Fabriano, at a distance of 2 km from each other. The distance from Fabriano ranges from 2 to 12 km. For completeness, a further source was defined exactly at the location of the reference epicentre, namely at 8.24 km from Fabriano. With this geometry, several groups of simulations were carried out for many different hypocentral depths, namely 2, 6, 10, 14, 20, 35, and 45 km, for a total of 49 sources. The last two depths, although not relevant to seismic hazard, have been included in order to predict the effects of a deep event, such as the March 26, 1998, $M_W \cong 5.4$ "Nocerino-Gualdese" earthquake. This earthquake had indeed an anomalous intensity distribution, since it was felt more at a large epicentral distance than in the epicentral area itself [14].

The source time history (Figs. 3a-c), i. e. the slip velocity function, is an unit Ohnaka's impulse [10]. This function is defined by only one parameter α. The Fourier amplitude spectrum (Fig. 3d) has a typical ω^2 decay. The proper value of the impulse parameter α is found by a best fit of the amplitude spectrum on the Gusev's source spectrum [1] corresponding to the seismic moment of the given earthquake (Fig. 3d). In particular, a

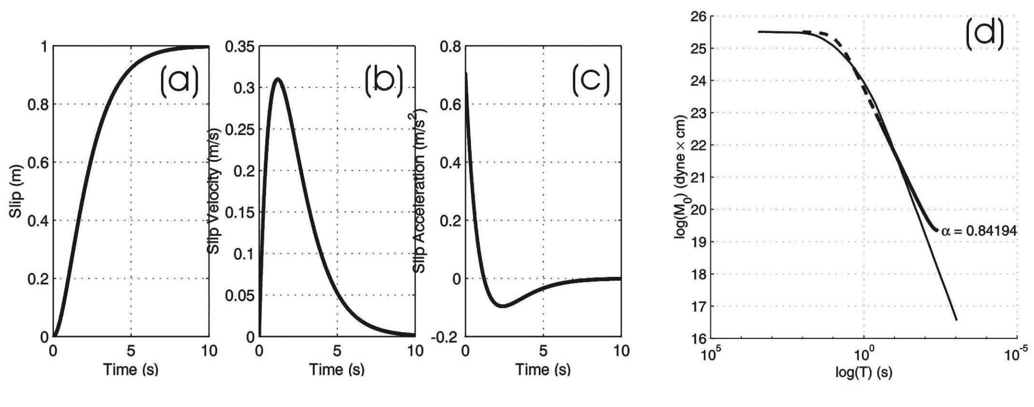

Figure 3. Fault slip time history. (a) Displacement, (b) velocity, (c) acceleration, and (d) Fourier's (dashed line) and Gusev's source spectrum corresponding to a M = 6.2 event (solid line).

value of $\alpha = 0.84194$ has been found for magnitude $M = 6.2$. The resulting corner frequency is $f_C = 0.134$ Hz.

The time step and the number of samples used in the numerical simulations have been set respectively at Δt = 0.04 s and N = 512. Computed seismograms have been low-pass filtered at f_{max} = 10 Hz, a frequency which corresponds to a dynamic range of about 10^4 dyna × cm in the source spectrum (Fig. 3d).
Seismograms computed with the point source (not shown here) features a strong impulsive shape [16], in particular at a short epicentral distance. On the other hand, both duration and complexity increases with distance. Fig. 4 shows the distribution of peak ground acceleration (PGA) versus the epicentral distance for all simulated hypocentral depths. The vertical component is usually lower than the horizontal one. For shallow sources, the horizontal peak amplitude decays rapidly with epicentral distance, and the largest values restrict to a rather narrow area. On the other hand, for deepest sources the horizontal amplitude decays very smoothly; the area of maximum ground shaking is much wider, and it moves farther from the epicentre. For the two most realistic depths – 6 and 10 km – the PGA occurs at an epicentral distance of about 2-4 km (≅ 0.8 g) and 4-6 km (≅ 0.45 g), respectively. However, at the distance corresponding to the reference event (8.24 km) this behaviour is reversed (0.21 g and 0.33 g for the source depths of 6 km and 10 km, respectively), a fact that I explain by the different kind of decay featuring deep and shallow sources, respectively. PGV features a behaviour completely similar to PGA [18].
While the broadening of the maximum ground shaking area is proportional to the source depth, its distance from the epicentre is mainly related to the fault mechanism. In particular, for the mechanism considered in this study, and assuming a homogeneous medium, the two shear-wave lobes directed toward the surface would radiate energy at vertical angles of 50° and 40°, in the NE and SW direction respectively. As the hypocentre becomes deeper, the S-wave lobes impinge the surface at larger epicentral distances. For instance, for the source depths of 10 and 45 km, the peak values would be found at about 7.5 and 35 km NE from the epicentre, and at 6.5 and 29 km in the SW direction, respectively. Obviously, with more realistic crustal models, that is with a velocity distribution decreasing smoothly toward the surface, these distances decrease owing to the progressive ray bending toward the surface. The values of 4-6 km predicted by the numerical simulation for the source depth of 10 km (Fig. 4) agree pretty well with the distance previously estimated in the SW direction. Moreover, numerical simulations predict that, for a source at a depth of 45 km, PGA may be 3-4 times larger at about 40 km from the epicentre than within the epicentral zone.
The above discussion may help to explain the anomalous distribution of the effects of the March 26, 1998, Mw ≅ 5.4 "Nocerino-Gualdese" earthquake. This event was localised a few kilometres NE of Nocera Umbra (PG) and at a depth of about 49 km. The earthquake was weakly felt in the epicentral area, while the maximum intensities (≅ 6) were observed towards the east, at several tens of kilometres from the epicentre [14].

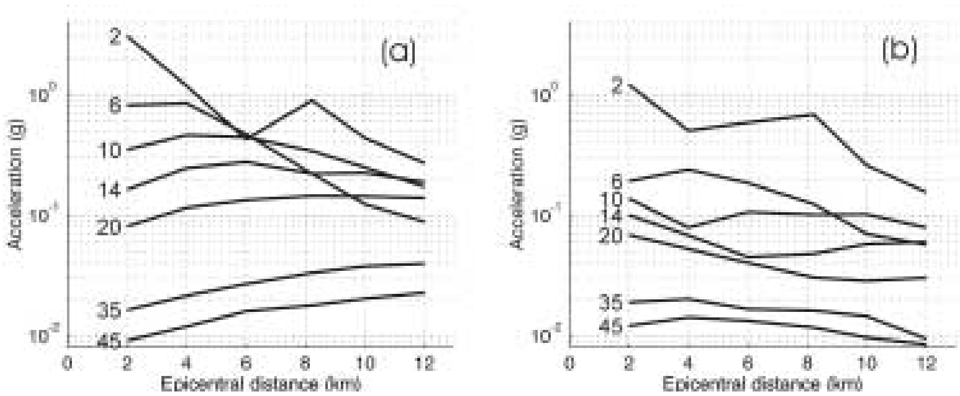

Figure 4. Point source. Peak ground acceleration vs. epicentral distance computed for different source depths (indicated by the numbers at the left of each curve (unit in km)). (a) Horizontal component, (b) vertical component. The horizontal component is the vector composition of E and N components.

EXTENDED SOURCE

The rupture along an extended fault segment has been simulated by decomposing the area into elementary sources, computing the wavefield generated by each source, and summing up each contribution synchronized in time to simulate the propagation of the rupture with the chosen velocity. The rupture kinematics is isotropic, with circular rupture fronts. In principle, for a given group of N elementary sources, it is possible to simulate N different ruptures simply by considering the nucleation from each elementary source. In this study, the extended source has been decomposed into 15 elementary sources defined on a 5×3 regular grid (Fig. 1), with a spatial step of 4 km in both fault plane directions. The size of the area associated with each elementary source is 4×4 km^2. The centre of the fault segment coincides with the reference epicentre. The source depths range over three values, namely 3.43 km (source en1-en5), 6 km (en6-en10), and 8.67 km (en11-en15). The average source depth is 6 km. The seismic moment of the elementary source is M_0 = 2.1 10^{24} dyna × cm, that is 1/15 of the total, and it corresponds to a magnitude of M = 5.5. The parameter of the source time history is α = 1.66846, and the resulting corner frequency is f_C = 0.265 Hz. The rupture velocity is equal to 0.8 times the average shear wave velocity, which is 3.5 km/s. The computational frequency band has been extended according to the decreased seismic moment. Compared to the point source, the time step has been halved to Δt = 0.02 s, while the total number of time steps has been increased to 1024. The total duration is again T = 20.48 s. Computed seismograms have been low-pass filtered to the cut-off frequency of f_{max} = 20 Hz. In this way, the dynamic range of the source spectrum has been maintained at the value of 10^4 dyna × cm (Fig. 3d).

The ground motion has been computed at 7 receivers. Six of them (receivers R1-R6 in Fig. 1) are aligned along the line connecting Fabriano to the epicentre with a spatial step of 2 km and at the epicentral distance ranging from 2 to 12 km. The seventh receiver is located in Fabriano itself (8.24 km from the reference epicentre). Fig. 5 shows the spatial distribution of the peak values. The envelopes have been computed taking into account all nucleating points but the shallowest ones (points en1-en5), since they are considered not realistic. The horizontal

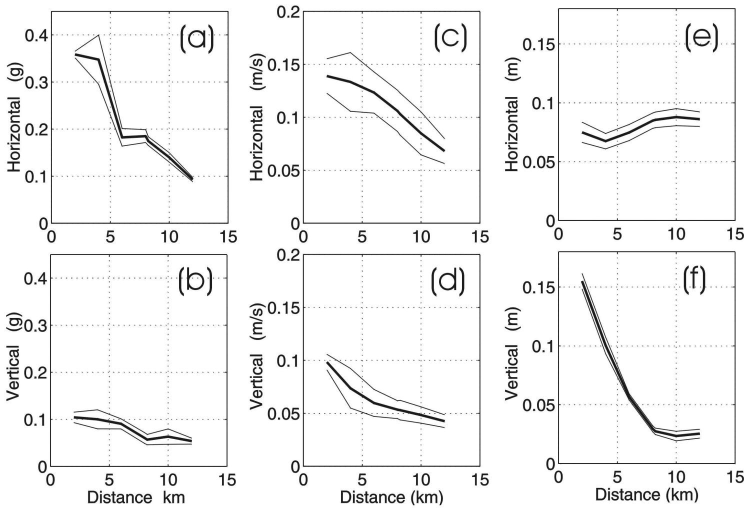

Figure 5. Extended source. Envelopes of peak ground motion vs. epicentral distance: (a, b) acceleration (PGA), (c, d) velocity (PGV), and (e, f) displacement (PGU). Thick and thin lines represent the average value, and the same plus/minus one standard deviation.

PGA is on average twice the vertical one. The highest (mean) value is about 0.36 g, and is predicted being about 2 km SW from the epicentre. Acceleration decays rapidly at increasing distances: at 12 km, the value is just 0.09 g. The first standard deviation is very low, just 10 % of the mean value. This suggests that changing the nucleation point produces only negligible effects on the peak values. The PGA predicted in Fabriano is 0.19±0.015 g e 0.07±0.01 g, for the horizontal and vertical components respectively. Finally, the peak values computed for the extended source are about half of those predicted for the point source at the depth of 6 km. Fig. 5b shows the distribution of the peak ground velocity (PGV). Compared to PGA, it features a lower decay rate and a higher balance between the horizontal and vertical components. PGV predicted in Fabriano is 0.1±0.02 m/s and 0.05±0.005 m/s, for the horizontal and vertical components respectively. Fig. 5c displays the distribution of peak ground displacement (PGU). The horizontal peak is almost independent of the epicentral distance. On the other hand, the vertical component feature higher values and a very steep decay.

Fig. 6 summarises seismograms computed in Fabriano for the different nucleations. Compare to those obtained for the point source, seismograms feature a remarkable complexity, and in particular: loss of impulsivity, smaller peak amplitude, longer duration (the train of direct waves lasts on average 8-10 s), and long period queue with a period $T \cong$ 2-2.5 s, likely due to surface waves. No noteworthy effects of rupture directivity can be observed. A possible explanation lies in the fact that all receivers are located on the hanging wall of the fault, and laterally to the fault trace. Their position is therefore far from the zones aligned with the directions of rupture propagation. According to this interpretation, the maximum ground motion should be felt in the fault strike direction - that is, either NW or SE of the source - and along the fault trace, NE of the epicentre. Fig. 7 displays the ground motion computed in Fabriano for a bilateral rupture nucleating at the centre of the fault segment (point en8). The acceleration amplitude spectrum is nearly flat up to the cut-off frequency of 20 Hz. The peak at 0.45 Hz corresponds to the long period coda evident in acceleration and velocity seismograms. The horizontal and vertical permanent displacements in Fabriano are negative and downward directed, respectively. Considering the given fault mechanism and PGU distribution in the SW direction (Fig. 7a), it can be argued that the area of maximum differential displacement falls in the direction of the fault trace, i. e. about 4-6 km NE of the reference

epicentre. This hypothesis agrees with the distribution of surface ruptures observed after the September-October, 1997, Colfiorito earthquake sequence [3].
Fig. 8 shows the response spectra of acceleration, velocity and displacement. Acceleration spectra feature a plateau in the low period band of 0.16-0.35 s; at higher periods the amplitude decays. The largest values are of about 0.21-0.24 g and 0.1-0.12 g for the horizontal and vertical component, respectively. The first standard deviation is within 20 % of the mean value. Predicted acceleration spectra compare very well with those computed independently by a probabilistic approach [15; Fig. 2] for a return period of 10 years. The deterministic ones predict values just a little lower than the others. However, both the general shape and plateau width are the same. The two components of the velocity spectra (Fig. 8b) feature a very different shape. The

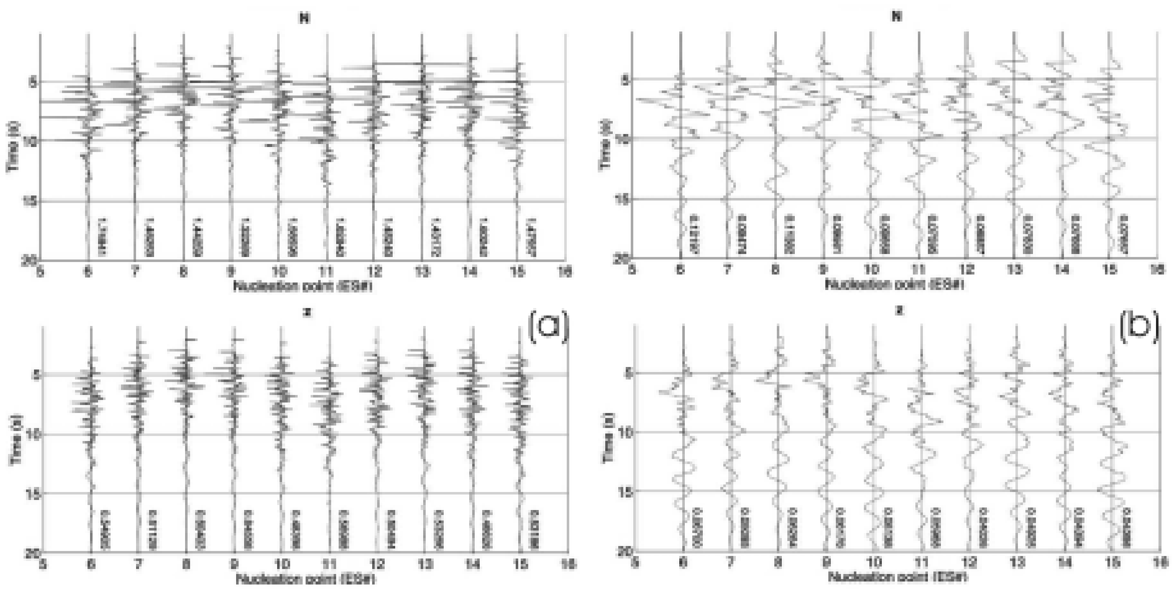

Figure 6. Extended source: seismograms computed in Fabriano for different rupture nucleations (en6-en15; see Fig. 1). (a) Acceleration (unit in m/s^2), and (b) velocity (m/s). Top and bottom panels display the North (N) and vertical (z) component, respectively. Peak values are written at the base of each trace.

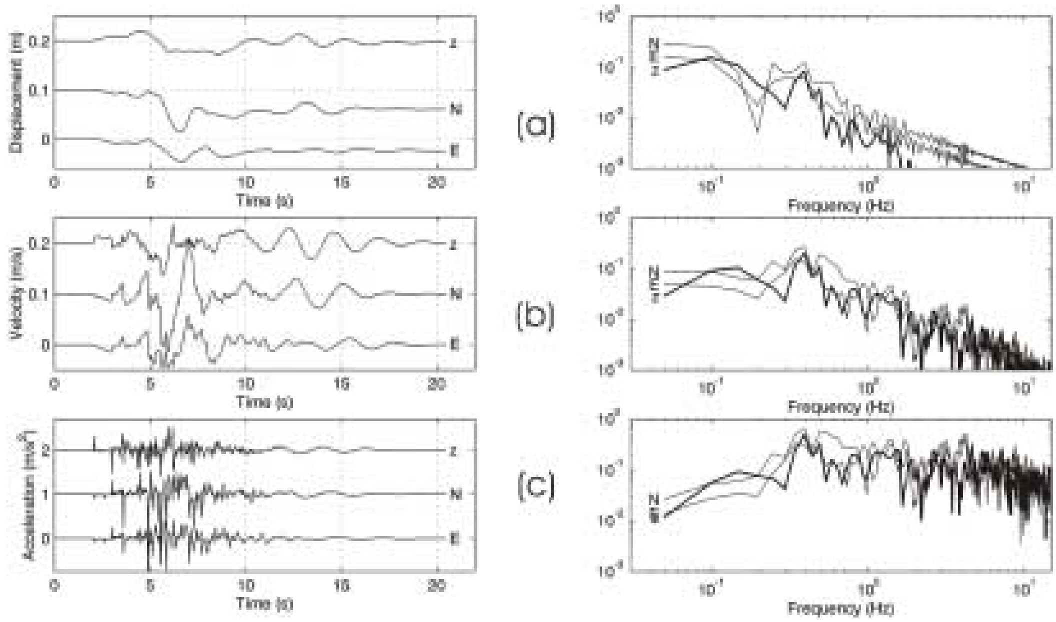

Figure 7. Seismograms and Fourier amplitude spectra of (a) displacement, (b) velocity, and (c) acceleration computed in Fabriano for a bilateral rupture (nucleation at point en8, see Fig. 1).

horizontal component features a wide plateau of large values (0.15-0.2 m/s) in the period interval 0.2-3 s. On the other hand, the vertical component features a sharp and narrow peak (0.14 m/s) at the period of about 2.5 s. This peak corresponds to the surface wave coda clearly visible in seismograms of Fig. 6.

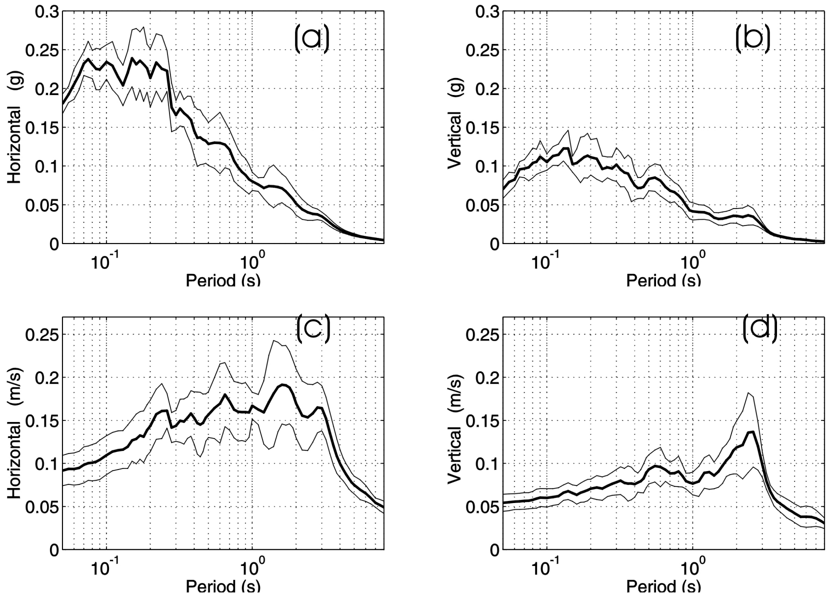

Figure 8. Response spectra (5% damping) of (a, b) acceleration, and (c, d) velocity computed in Fabriano. Other details as in Fig. 5.

CONCLUSIONS

The main result of this study is a *suite* of synthetic seismograms and response spectra characteristic for the town of Fabriano and a scenario earthquake of intermediate size, such as the 24 April, 1741, M = 6.2 "Fabrianese" earthquake. Results have been analysed mainly in terms of ground motion peak values, and Fourier and response spectra. For instance, acceleration predicted in Fabriano ranges between 0.2-0.25 g for frequencies higher than 3 Hz, with a horizontal PGA of about 0.19 g. The response spectra and peak values computed with an extended source model are consistent with those computed independently by a probabilistic approach.

The effect on the surface ground motion produced by changing both source position and depth, as well as the direction of the rupture on the fault plane, has also been analysed. It has been found that by increasing the hypocentral depth, the area of maximum ground motion moves away from the epicentre. This could explain, at least in part, the anomalous intensity distribution of a recent, deep event, the March 28, 1998, M_W = 5.4 "Nocerino-Gualdese" earthquake, which was felt with more intensity at several tens of kilometres from the epicentre than in the epicentral area itself.

Besides the specific ground motion values - easily read throughout the text - the importance of the choice and constraints imposed on the reference earthquake must be noted. Estimates are indeed very sensitive to both source-site location and to fault mechanism. On the other hand, a sensitivity analysis ([16], not included here) shows that details on the structural model play only a secondary role, in view of the estimation of the reference ground motion. Therefore, as far as the general methodology is concerned, it seems worth strengthening the validity of the approach by weakening some constraints imposed on the reference earthquake, for instance, by taking into account more than one fault mechanism and hypocentral location.

Finally, despite the constraints applied to the choice of the reference earthquake, this study confirms that the deterministic computation of the reference ground motion is of great value, since the results are always consistent with the underlying physics and assumptions specific for the study area, and they have several details that could not be reproduced by a different approach.

ACKNOWLEDGEMENTS

Fig. 1 was made by the GMT software. Synthetic seismograms have been computed by the *Wavenumber Integration Method*, with the computer code of the package *Computer Programs in Seismolgy* developed by R. B. Herrmann at St. Louis University (Herrmann, 1996). The work was partly funded by National Research Council – National Group for the Defence Against Earthquakes (CNR-GNDT), research grant n. 98.03227.PF54. The results of this study are available either from the author upon request or by anonymous-ftp at: eprioloftp.ogs.trieste.it (directory: pub/Umbria-Marche/Fabriano).

REFERENCES

Aki, K. (1985), "Strong motion seismology", in Erdik, M. and Toksöz, M.N. (eds.): "Strong ground motion seismology", NATO ASI Series Proc. of the NATO Adv. Study Inst. on Strong Motion Seism., Ankara, Turkey, June 10-21, 1985. Reidel Pub. Comp.

Amato, A., Azzara, R., Basili, A., Chiarabba, C., Cimini, G.B., Cocco, M., Di Bona, M., Margheriti, L., Mele, F., Selvaggi, G., Boschi, E., Bittarelli, G., Chiaraluce, L., Piccinini, D., Ripepe, M., Courboulex, F., Deschamps, A., and Gaffet, S. (1997), "Studio sismologico preliminare della sequenza di Colfiorito", in Boschi, E., and Cocco, M. (eds.): "Studi preliminari sulla sequenza sismica dell'Appennino Umbro-Marchigiano del settembre-ottobre 1997", Publication of the Istituto Nazionale di Geofisica n. 593, Istituto Nazionale di Geofisica, pp. 1-9 (in italian).

Basili, R., Bosi, V., Galadini, F., Galli, P., Meghraoui, M., Messina, P., Moro, M., Sposato, A. (1998), "The Colfiorito earthquake sequence of September-October 1997: surface breaks and seismotectonic implications for the Central Apennines (Italy)", J. Earthq. Eng., 2 (2), 291-302.

Boncio, P. and Lavecchia, G.(1998), "I terremoti di Colfiorito (Appennino umbro-marchigiano) del settembre-ottobre 1997: contesto tettonico e prime considerazioni sismogenetiche". In: "Note relative al terremoto dell'Umbria-Marche del settembre 1997". CNR-GNDT, Annual Conference; Roma, 19-21 October, 1998. 1-10 + 5 Figs (in Italian).

Cattaneo, P., Augliera, P., De Luca, G., Gorini, A., Govoni, A., Marcucci, S., Michelini, A., Monachesi, G., Spallarossa, D., Trojani, L., and XGUMS (submitted), "The 1997 Umbria-Marche (Italy) earthquake sequence: analysis of the data recorded by the local and temporary networks", J. of Seismology.

Cello, G., Mazzoli, S., Tondi, E., Turco, E. (1997). "Active tectonics in the central Apennines and possible implications for seismic hazard analysis in peninsular Italy". Tectonophysics, 272, 43-68.

Costa, G., Panza, G.F., Suhadolc, P., and Vaccari, F. (1993). "Zoning of the Italian territory in terms of expected peak ground acceleration derived from complete synthetic seismograms". J. Appl. Geophys., 30, 149-160.

Deschamps, A., Scarpa, R. and Selvaggi, G. (1989). "Analisi sismologica del settore settentrionale dell'Appennino Umbro-Marchigiano". Proceedings of the VIII Convegno del Gruppo Nazionale di Geofisica della Terra Solida, 1, pp. 9-16 (in Italian).

Galadini, F., Galli, P., Leschiutta, I., Monachesi, G., and Stucchi, M. (submitted), "Active tectonics and seismicity in the area of the 1997 earthquake sequence in Central Italy: a short review". J. of Seismology.

Herrmann, R.B. (1996), "Computers program in seismology. Volume VI: wavenumber integration", Dep. of Earth and Atmospheric Sciences; Saint Louis University. Version 3.0 edition.

Lavecchia, G., Brozzetti, F., Barchi, M., Menichetti, M., and Keller, J.V.A. (1994), "Seismotectonic zoning in east-central Italy deduced from an analysis of the Neogene to present deformations and related stress fields", Geol. Soc. Am. Bull., 106, 1107-1120.

Marcellini, A. (Scient. Resp.) (1998), "Progetto Microzonazione Sismica Umbria-Marche. Programma di lavoro", Web site: http://seism.irrs.mi.cnr.it/Ital/homeum.html, Report n. 2 (in italian).

Monachesi, G., and Stucchi, M. (Eds.) (1997), "DOM4.1, an intensity database of damaging earthquakes in the Italian area", CNR-GNDT, Milano, 2 vols., 1052 pp., Web site: http://emidius.itim.mi.cnr.it/DOM/home.html

Monachesi, G., Castelli, V., Coppari, H., and Stucchi, M. (submitted), "La storia sismica di Fabriano", In: Marcellini, A., and Tiberi, P. (eds.) "Fabriano: la microzonazione sismica", pp. 200 (in Italian).

Peruzza, L. (1998), "Valutazione del moto sismico di riferimento. Approccio probabilistico", Progetto microzonazione Umbria-Marche. CNR-GNDT. U. O. OGS-Trieste. Rel. OGS/28/98-OGA/7 (in Italian).

Priolo, E. (1999), "Calcolo deterministico del moto di riferimento a Fabriano", Progetto microzonazione Umbria-Marche. CNR-GNDT. U. O. OGS-Trieste. Rel. OGS/5/99/DGL/3 (in Italian).

Rovelli, A., Bonamassa, O., Cocco, M., Di Bona, M., Mazza, S. (1988), "Scaling laws and spectral parameters of the ground motion in active extensional areas in Italy", Bull. Seis. Soc. Am., 78, 530-560.

Scandone, P., and Meletti, C. (1996), "Zonazione sismogenetica del territorio nazionale ed aree limitrofe (ZS4)". CNR-GNDT. Web site: http://emidius.itim.mi.cnr.it/GNDT/ZONE/zone_sismo.html

Wells, D. L., and Coppersmith, K. J. (1994), "New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement", Bull. Seism. Soc. Am., 84, 974-1002.

Westaway, R. (1992), "Seismic moment summation for historical earthquakes in Italy: tectonic implications", J. Geophys. Res., 97 (B11), 15437-15464.