7. MACROSEISMIC FIELD MODELLING USING SYNTHETIC SEISMOGRAMS

Karim Aoudia(1), *Angela Saraò*(2)

(1) Abdus Salam International Centre for Theoretical Physics, Trieste
(2) Dipartimento di Scienze della Terra, Università di Trieste

7.1 Introduction

One of the major sources of information for the definition of seismic risk scenarios are macroseismic data, often the only available data for historical earthquakes. For instrumental earthquakes, the extent of macroseismic data and the abundance of experimental records (strong ground motion and VBB waveforms) that permit a good knowledge of the seismic source and structural parameters, allow a better understanding of the nature of the ground shaking and the resulting damage patterns.

In this report we test our macroseismic field modelling methodology for postulated sources using synthetic seismograms against the Umbria-Marche experimental ground motion data set and observed macroseismic data. The observed intensities can be converted into accelerations (Decanini et al., 1995) or into velocities and displacements (Panza et al., 1999a) using the available relations, and then compared with the synthetic data, that are dependent both on the source parameters and on the structural model used in the computations of the time series. This work builds upon the realistic modelling of strong motion for pre-disaster orientation in earthquake prone-areas (Panza et al., 1996; Panza et al., 1999b), and continues the investigations of source, path, and site effects.

The Umbria-Marche earthquake sequence started in September 26, 1997 and took place in a complex deforming zone, along a normal fault system in the central Apennines (Fig. 1). In this report we focus on the two September 26 crustal events (Mw 5.7 at 00:33 and Mw 6.0 at 09:40) that have generated extensive ground motion and caused great damage in urban areas.

We determine the regional and local structural models by analysing VBB and strong-motion registrations (Fig. 1). This will provide calibration data for constraining regional and local velocity models, for retrieving the source parameters and, ultimately, for better understanding the strong motion recordings.

Using only two three-component stations we compute the seismic moment tensor for the two September 26 crustal events. The knowledge of the physical process of the

---

Contributo dell’UO UNITS
International Centre for Theoretical Physics, Strada Costiera 11, 34100, Trieste
Responsabile: P. Suhadolc
Contratto n.98.03238.PF54
e-mail 1° autore: aoudia@dst.univ.trieste.it

two September events is used to model the strong ground motion by computing synthetic seismograms (up to 1 Hz) by the modal summation technique (Panza, 1985; Florsch et al., 1991). Detailed description and application of the methodology can be found in Panza et al. (1996). We generate 1Hz maps of seismic displacement and velocity fields using scaled point sources and extended sources to yield the most informed estimates of ground motion. The maps are discretized according to the regression intensity-displacement, computed for the Italian territory by Panza et al. (1999a). Since the two earthquakes were close in time and space, we compute the seismic wave-field corresponding to the maximum of both events and investigate how the related pattern compares with the cumulative damage effects as reported in the observed macroseismic data (Monachesi et al., 1997). To validate our modelling we compare synthetic seismograms with the experimental records and determine ground motion parameters that correlate best with damage.

7.2 Source Parameters

We compute the seismic moment tensor by waveform inversion for the two main events of the September sequence. We use only two three-component stations, Trieste and l'Aquila (Fig. 1). The inversions are performed considering structural models retrieved from frequency time analysis and the EurI-data set (Du et al., 1998) for Trieste-epicenter path, while the model for the l'Aquila-epicenter path is taken from literature (Costa et al., 1993).

The method we apply has been developed by Sileny and Panza (1991) and Sileny et al. (1992). The inversion does not constrain the solution with a priori assumptions and consists of two main steps. The first one is linear and inverts data using elementary seismograms, computed by modal summation (Panza, 1985; Florsch et al., 1991) for each moment tensor component, to calculate the six moment rate functions. In the second step, after the waveform inversion, the information on the focal mechanism and the duration of the energy release are extracted from the six components of the moment tensor. The moment rate functions are factored into an average moment tensor and corresponding source time function. The hypocentre is not fixed and can move inside a pre-defined volume while in this study we keep fixed the epicentre and perform several trials using all the epicentral locations available in the literature (Ekstrom et al., 1998; Amato et al., 1998; Cattaneo et al., 1999).

In all the inversion trials the focal mechanisms are quite stable while slight varia-

Tab. 1 - Source parameters.

Event Date, hour	Lat-Long (°)	Depth (km)	M0 (N·m)	Strike (°)	Dip (°)	Rake (°)	Half Duration(s)
26.09.97; 00:33	43.02 - 12.89	5	$5.3 \cdot 10^{17}$	156	38	289	2.0
26.09.97; 09:40	43.02 - 12.85	7	$9.5 \cdot 10^{17}$	142	39	273	3.2

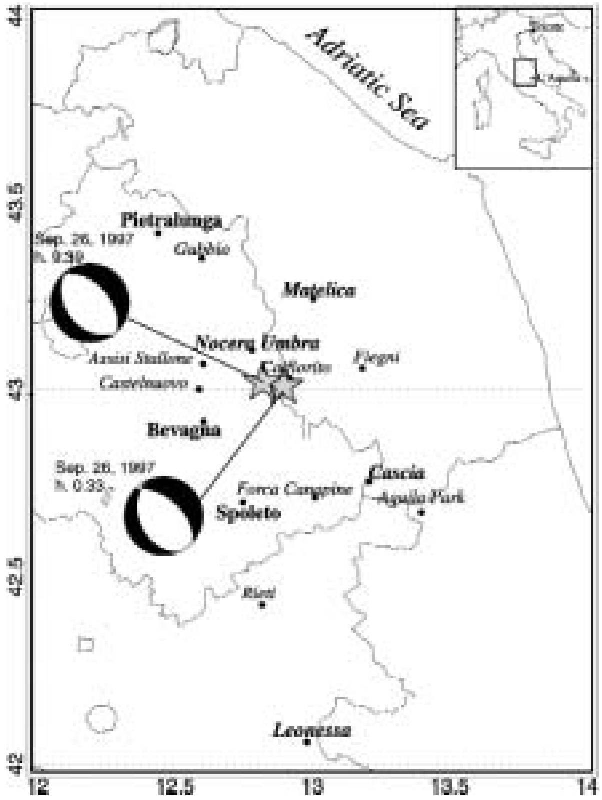

Fig. 1 - Epicentral map of the the studied main events and stations used in our study: the stations in bold are used for the S-wave velocity inversion, the stations in italic for the strong motion modelling. In the inset the frame indicates the location of the region under study. The stations of l'Aquila and Trieste are used in the inversion of the moment tensor.

tions in the data correlation and in the hypocentral location are observed. The solutions we show (Fig. 1) are obtained using the epicentral coordinates of Cattaneo et al. (1999). The computed source parameters are reported in Tab. 1.

7.3 Scaled-source Modelling

The double-couple point-source is defined by the focal depth and by the three parameters that specify the fault plane solution: strike, dip and rake. We compute complete synthetic seismograms, up to 1 Hz, on a receiver grid for a scaled source according to the spectral scaling law proposed by Gusev (1983) as reported in Aki (1989). The structural models used for the calculation of the synthetic seismograms are the regional ones valid for central Italy (Costa et al., 1993) where the uppermost velocities (2 km) are in good agreement with the inverted group-velocity dispersion curves. The radial and the transverse components of motion, calculated at the various sites of interest, i.e. the sites where macroseismic observations are available, are vectorially summed and the maximum

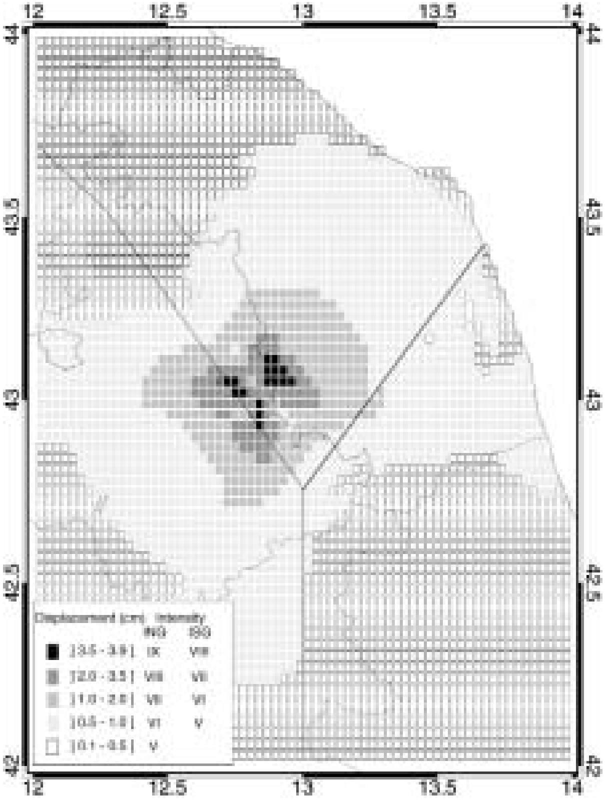

Fig. 2 - Displacement wave-field computed for the Umbria-Marche September main shock. The area is subdivided into three average velocity models (Costa et al., 1993). The intensity estimates are obtained using the relations by Panza et al. (1999a) for ING (Boschi et al., 1995) and ISG (Molin et al., 1996) data.

amplitudes of such quantities are used to represent the spatial distribution of the ground shaking.

Using the source parameters reported in Tab. 1 we generate maps of seismic displacement and velocity fields for the two first events of September 26, 1997. The seismic field is discretized according to the regression intensity-displacement and intensity-velocity, computed for the Italian territory by Panza et al. (1999a).

Fig. 2 shows the case where an excellent agreement between theoretical and observed data is achieved. In our trials we test different epicentral locations and vary the focal depth from 5 to 10 km by 1 km increment. We also consider the maximum wave-field resulting from both earthquakes, since they were close in time and space. Our results show that the source depth has a strong influence on the pattern of the computed seismic wave-field. The seismic field of the largest event of 9:40 (Mp = 6.1, NEIC), dominates over the one of the 00:33 event (Mp = 5.7, NEIC). The computed values of displacement and velocity mimic reasonably well the observed intensity data points (Tab. 2) when using the epicentral locations of Cattaneo et al. (1999) with a depth of 7 km. The agreement between the pattern and shape of the theoretical field with the observed macroseismic data is achieved better when considering displacement rather than velocity, sugge-

Tab. 2 - Observed intensity at different strong motion recording stations vs synthetic ground motion (displacement and velocity). Theoretical intensity is obtained from point-source displacement or velocity using the relations by Panza et al. (1999a) on the maximum observed intensity given by Boschi et al., 1995 (ING), and Molin et al., 1996 (ISG). Note the good agreement between point source and extended source strong motion parameters. The agreement between the pattern and shape of the theoretical wave-field (see Fig. 2) with the observed macroseismic data is achieved better when considering displacement (shaded column) rather than velocity.

Recording stations	**Obs. Int.**	**Displacement (cm)**		**Velocity (cm/s)**		**Theoretical Intensity**			
		Point source	**Extended source**	**Point source**	**Extended source**	**ING**	**ISG**	**ING**	**ISG**
Colfiorito	IX	3.83	3.67	9.35	11.3	IX	VIII	IX	VIII
Nocera Umbra	VIII	1.73	1.86	5.79	4.00	VII	VII	VIII	VIII
Gubbio	VI	1.55	0.92	3.02	3.30	VII	VII	VII	VII
Matelica	VII	1.24	1.14	1.90	2.70	VII	VI	VI	VI
Fiegni	VIII	1.28	1.39	1.74	2.5	VII	VI	VI	VI
Forca Canapine	VI	0.50	0.20	0.74	0.9	VI	-	V	-
Cascia	VI	0.69	0.19	1.09	0.90	VI	-	VI	VI
Leonessa	VI	0.53	0.15	0.68	0.53	VI	-	V	-
Castelnuovo	VIII	1.77	1.60	3.27	2.89	VII	VII	VII	VII
Assisi Stallone	VII	1.80	1.33	3.34	3.19	VII	VII	VII	VII
Rieti	V	0.58	0.15	0.64	0.35	VI	-	V	-
Aquila Park	V	0.33	0.14	0.65	0.38	V	-	V	-

sting that, in this case, relatively long periods effects correlate better with the damage distribution.

7.4 Extended source modelling

Synthetic three-component accelerograms are computed for an extended source using the method of multimodal summation (Panza, 1985; Panza and Suhadolc, 1987). The source mechanisms are reported in Tab. 1, and the fault is assumed as rectangular (10/9 km) discretized into square cells. The rupture model is a discrete analog of a Haskell-type model, with rupture propagating at a speed of 70% of the shear wave velocity of the medium (Saraò et al., 1998). At each cell of the grid we assume a point source which generates a seismogram. The point-source seismograms are then delayed according to the rupture propagation times and properly scaled to take into account the local complexities of the energy release. Finally, at each recording station, the point-source contribution is added to construct the complete synthetic seismogram. In our simulation we assume constant slip on the fault and to avoid sharp slip discontinuities, the slip distribution is tapered by a 2-D cosine function at the edges of the fault.

We compute velocities and displacements up to 1 Hz for some of the stations plotted in Fig. 1. For each station the maximum velocity and displacement value is reported in Tab. 2. These values agree reasonably well with the scaled point-source estimates in the interval of intensity ranges defined by Panza et al. (1999a).

7.5 Conclusions

Theoretical intensity values obtained from scaled source displacement or velocity strong motion using the relations by Panza et al. (1999a) compare very well with the observed macroseismic data points.

The agreement between the pattern and shape of the theoretical wave-field with the observed macroseismic data is achieved better when considering displacement rather than velocity, suggesting that, in this case, relatively long periods effects correlate better with the damage distribution.

The scaled source and extended source simulations (up to 1 Hz) predict comparable values of strong motion within the interval of intensity ranges defined by Panza et al. (1999a). Scaled source modelling is sufficient to make a realistic prediction of the ground motion. Such methodology may find a good application in understanding source processes of historical earthquakes either by using a scaled-point source when no data is available on the finiteness and complexity of the causative fault or by using the extended source in case where geology provides enough data to constrain a reasonable fault model.

The maps of seismic wave-field can be generated and posted in minutes after moderate and large events occur. These maps are designed to be useful for Emergency Service Workers, indicating areas likely to have suffered extensive shaking damage.

Acknowledgements. This research has been made possible mainly by CNR 97.00540.PF54 and CNR 98.03238.PF54 funds (Gruppo Nazionale per la Difesa dai Terremoti). It is a contribution to the UNESCO IGCP 414 Project “Realistic Modelling of Seismic Input for Megacities and Large Urban Areas”. We acknowledge support by UNESCO-UVO-ROSTE 875.669.9.

References

Aki, K. (1989): Strong motion seismology. In: M.Ö. Erdik and M.N. Toksöz (eds.), *Strong Ground Motion Seismology*, NATO ASI Series, Series C: Mathematical and Physical Sciences, D. Reidel Publishing Company, Dordrecht, vol. 204, 3-39.

Amato A., Azzara R., Chiarabba C., Cimini G. B., Cocco M., Di Bona M., Margheriti L., Mazza S., Mele F., Selvaggi G., Basili A., Boschi E., Corboulex F., Deschamps A., Gaffet S., Bittarelli G., Chiaraluce L., Piccinini D. and Ripepe M. (1998): The 1997 Umbria-Marche, Italy, earthquake sequence: a first look at main shocks and aftershocks. *Geophys. Res. Lett.*, **25(15)**, 2861-2864.

Boschi, E., Favali, P., Frugoni, F., Scalera, G. and Smriglio, G. (1995): Mappa della massima intensità macrosismica risentita in Italia. Istituto Nazionale di Geofisica, Roma.

Cattaneo, M., Augliera, P., De Luca, G., Gorini, A., Govoni, A., Marcucci, S., Michelini, A., Monachesi, G., Spallarossa, D., Trojani, L. and XGMUS (1999): The 1997 Umbria-Marche

(Italy) earthquake sequence: analysis of the data recorded by the local and temporary networks. *J. Seism.*, submitted.

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.

Decanini, L., Gavarini, C. and Mollaioli, F. (1995): Proposta di definizione delle relazioni tra intensita' macrosismica e parametri del moto del suolo. Atti del 7° Convegno L'ingegneria sismica in Italia, 1, 63-72.

Du, Z. J., Michelini, A. and Panza, G. F. (1998): EurID: a regionalised 3-D seismological model of Europe". *Phys. Earth Planet. Int.*, **105**, 31-62.

Ekström, G., Morelli, A., Boschi, E. and Dziewonski, A. (1998): Moment Tensor Analysis of the Central Italy Sequence of September-October 1997. *Geophys. Res. Lett.*, **25**, 1971-1974.

Florsch, N., Fäh, D., Suhadolc, P., and Panza, G.F. (1991): Complete Synthetic Seismograms for High-Frequency Multimode SH-waves. *Pure and Appl. Geophys.*, **136**, 529-560.

Gusev, A.A. (1983): Descriptive statistical model of earthquake source radiation and its application to an estimation of short period strong motion. *Geophys. J.R. Astron. Soc.*, **74**, 787-800.

Molin, D., Stucchi, M. and Valensise, G. (1996): Massime intensità macrosismiche osservate nei comuni italiani. GNDT - ING - SSN, Roma.

Monachesi G., Camassi R., e Molin D. (1997): Rilievo macrosismico degli effetti dei terremoti del 26 settembre 1997 e seguenti (aggiornato al 20/10/1997). Internet: http://emidius.itim.mi.cnr.it/GNDT/ T19970926/rilievo1020.html

Panza, G.F. (1985): Synthetic seismograms: the Rayleigh waves modal summation. *J. Geophys.*, **58**, 125-145.

Panza, G.F. and P., Suhadolc (1987): Complete strong motion synthetics. In: B. A. Bolt (ed.) *Seismic Strong Motion Synthetics.* Computational Techniques, 4, Academic Press, Orlando, 153-204.

Panza, G.F., Vaccari, F., Costa, G., Suhadolc, P. and Fäh, D. (1996): Seismic input modelling for zoning and microzoning. *Earthquake Spectra*, **12**, 529-566.

Panza, G.F., Vaccari, F. and Cazzaro, R. (1999a): Deterministic seismic hazard assessment. In: F. Wenzel et al. (Eds), *Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation*. Kluwer Academic Publishers, The Netherlands, 269-286.

Panza, G.F., Vaccari, F. and Romanelli, F. (1999b): The IUGS-UNESCO IGCP Project 414 : Realistic modeling of Seismic Input for Megacities and Large Urban Areas. *Episodes*, **22**, 26-32.

Saraò, A., Das, S. and Suhadolc, P. (1998): Effect of non-uniform station coverage on the inversion for earthquake rupture history for a Haskell-type source model. *J. Seism.*, **2**, 1-25.

Sileny, J. and Panza, G.F. (1991): Inversion of seismograms to determine simultaneously the moment tensor components and source time function for a point source buried in a horizontally layered medium. S*tudia Geoph. Geod*., **35**, 166-183.

Sileny, J., Panza, G.F. and Campus, P. (1992): Waveform inversion for point source moment tensor retrieval with optimization of hypocentral depth and structural model. *Geophys. J. Int.*, **108**, 259-274.