SHAKEMAP METHODOLOGY BASED ON FOURIER AMPLITUDE SPECTRA AND ITS APPLICATION FOR THE CASE OF VRANCEA EARTHQUAKES IN ROMANIA

V. Sokolov[1], M. Boese[2] and F. Wenzel[3]

[1] *Geophysical Institute, Karslruhe University, Karlsruhe, Germany*
[2] *Seismological Laboratory, California Institute of Technology, Pasadena, CA, USA*
[3] *Geophysical Institute, Karslruhe University, Karlsruhe, Germany*
Email: Vladimir.Sokolov@gpi.uni-karlsruhe.de

ABSTRACT :

Shake maps are generated within a few minutes on a routine basis by extrapolation ground motion parameters such as PGA, PGV, response spectra, and computed intensity from observational sites equipped with accelerometers with distances in the range of kilometers to tens of kilometers between them. Extrapolation is based on empirical hard-rock attenuation relations, geological classification of the sites, and on empirical relations of ground motion amplification for a given geological class. We suggest a pure seismological approach based on Fourier amplitude spectrum (FAS) that can be used in most cases and that allows obtaining site-dependent assessment in terms of various ground motion parameters. First, source scaling and attenuation models for FAS are evaluated using recordings obtained on rock stations. Second, the site effect at non-rock stations is analyzed as ratios between the spectra of observed records and the obtained spectral models. Third, the generalized site amplification functions are constructed for typical soil conditions. Fourth, using stochastic technique, the site-dependent attenuation models are constructed to be used directly in shake map generation. The method is applied for the case of intermediate-depth (70-140 km) earthquakes of the Vrancea (Romania) source zone, which produce the most significant seismic hazard to Romania, including the city of Bucharest, and its neighboring countries. We modeled ground motion parameters distribution for major Vrancea earthquakes occurred during the last century, e.g November 10, 1940 (M = 7.7), and March 4, 1977 (M = 7.4). The theoretical data were compared with available observations.

KEYWORDS: Shake map, Vrancea region, strong ground motion, prediction equations

1. INTRODUCTION

Seismic hazard for almost half of the territory of Romania is determined by the Vrancea seismic region, which is situated beneath the southern Carpathian Arc in Romania. The region is characterized by a high rate of occurrence of large earthquakes in a narrow focal zone. The epicentral area is confined to about 60 x 20 sq. km and the seismic activity ranges within an almost vertical stripe in depths between 70 and 170 km (Figure 1). During the last century four major Vrancea earthquakes occurred on November 10, 1940 (M_W = 7.7), March 4, 1977 (M_W = 7.4), August 30, 1986 (M_W = 7.2) and May 30, 1990 (M_W = 6.9). The former two lead to disastrous impact on Romanian territory.

Analysis of the seismic intensity (Figure 2) and instrumental data from the intermediate-depth Vrancea earthquakes revealed several peculiarities of earthquake effects (e.g. Radu et al., 1979; Mandrescu and Radulian, 1999; Mandrescu et al., 1988; Moldovan et al., 2000), namely: (a) the earthquakes affect very large areas with a predominant NE-SW orientation; (b) the local and regional geological conditions can control the variation of amplitudes of earthquake ground motion to a larger degree than magnitude or distance. The strong ground motion parameters exhibit a large variability. A set of macroseismic data for these events is available from the Romanian, the Bulgarian, the Moldavian and Ukrainian territory. However, the 1977 earthquake was recorded in Romania by only one accelerograph located in Bucharest. The other strong events (1986 and 1990) produced about 30 free-field analog records each (e.g. Oncescu et al., 1999). Romania may be considered as one of the region with a lack of instrumental strong-motion data. The peculiar features of the Romanian seismicity do not allow performing a proper selection of appropriate ground-motion model developed for the other region.

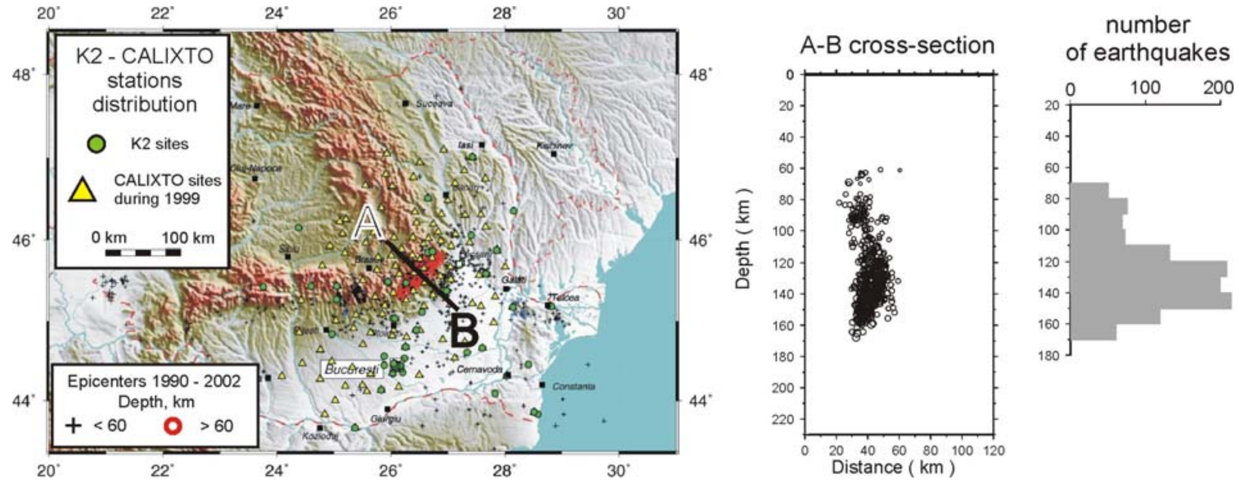

Figure 1. Epicentral map of the Vrancea earthquakes (circles, 1990-2002), location of seismic network, and depth distribution of hypocenters.

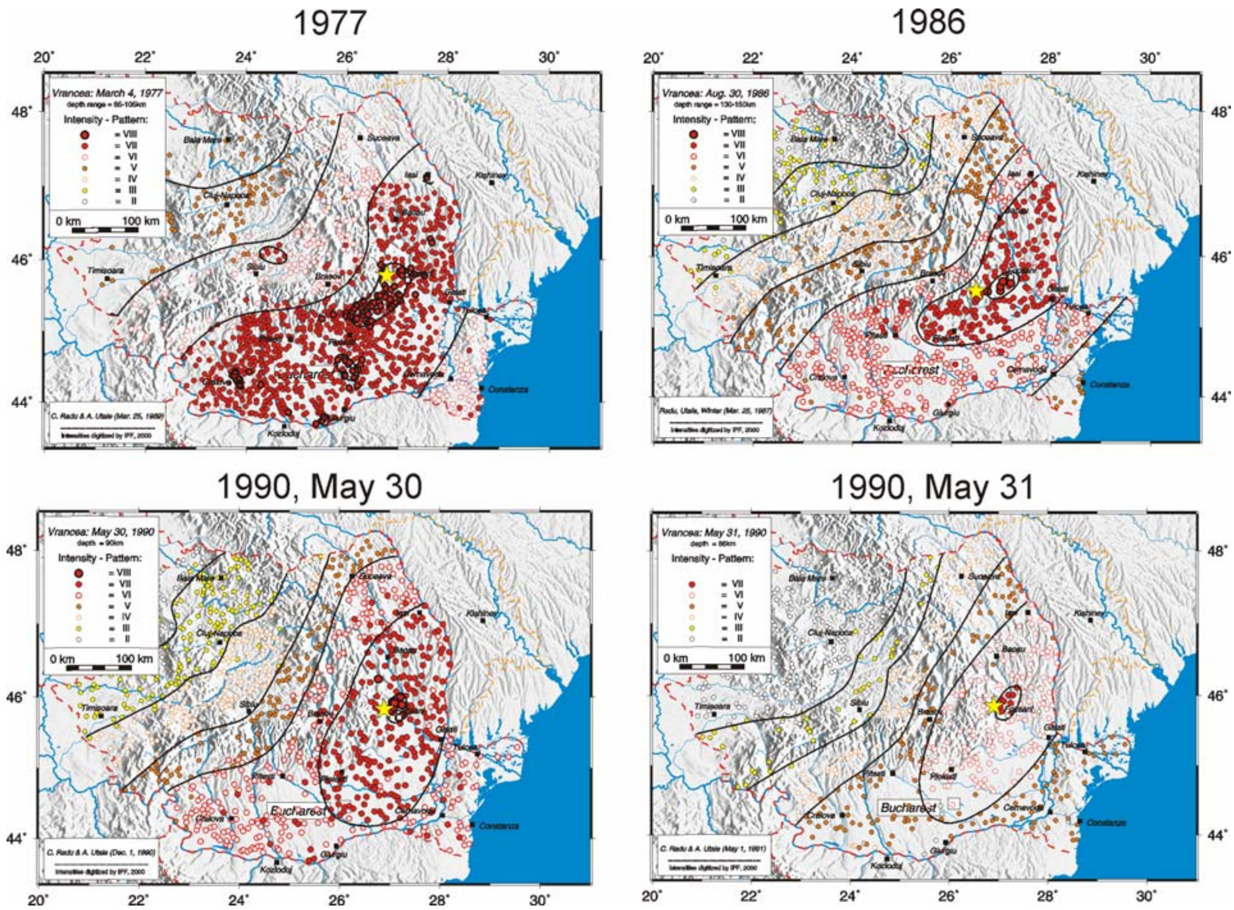

Figure 2. Observed distribution of macroseismic intensity during the large Vrancea earthquakes.

Romania is characterized by a widely spaced digital seismic network (about 40 accelerometers) covering mainly the SE part of the country. Also there is lack of understanding of the relations between geological near-surface structure and ground motion amplification. Therefore the ShakeMap methodology should be based only on available seismological information.

2. METHOD

The source scaling and attenuation models for Fourier Amplitude spectra (FAS), as well as the site amplification functions, were evaluated on the basis of accumulated earthquake ground motion data. Several hundred records from about 100 small and moderate-size earthquakes ($M_W \leq 6.0$) obtained by the permanent (K2) accelerometer network (Figure 1, see Bonjer et al., 2000), which was installed during recent years jointly by the Collaborative Research Center 461 “Strong Earthquakes” of Karlsruhe University and the National Institute for Earth Physics, Bucharest. Several earthquakes were also registered in 1999 by a temporary network during the CALIXTO (Carpathian Arc Lithospheric X-Tomography) experiment (Martin et al., 2006). The strong-motion data (several tens analog accelerograms) from the large Vrancea earthquakes of 1977, 1986 and 1990 (M_W 7.4, 7.1, 6.9, and 6.3) were also used.

Analysis of the earthquake ground motion data showed (Sokolov et al., 2005) that for intermediate-depth earthquakes in the Vrancea zone the single-corner-frequency spectral model may be used for hard rock sites. In general, the stress parameter $\Delta\sigma$, which controls high-frequency spectral amplitudes, increases with magnitude from 20-30 bars for $M_W \leq 3.5$ up to 200-250 bars for M_W 4.8-5.3 and up to 600-1000 bars for the case of large ($M_W > 6.0$-6.5) events. The generalized three-layer Q-model is applied as $Q(f) = 150 f^{0.8}$ for depth from 200 km to 100 km; $Q(f) = 400 f^{0.8}$ for depth from 100 km to 40 km, and $Q(f) = 100 f^{0.8}$ for depth less than 40 km (Radulian et al., 2000).

The site-specific amplification functions were evaluated for several locations (stations of the K2 and CALIXTO networks) in Romania. The local soil conditions vary from metamorphic rock to thick and water-saturated sedimentary formation. The amplification functions were estimated within a frequency range of 0.3-0.5 Hz – 12-15 Hz using two so-called “non-reference” techniques. One is a modification of the well-known horizontal-to-vertical Fourier spectral ratio (HVSR) of the S-wave phase (Lermo and Chavez-Garcia, 1993). In the second one, the site-specific amplification is evaluated as ratio between the observed spectra and the developed “very hard rock” spectral (VHR) model (Sokolov et al., 2004a, 2005). We used a combined variant for site-dependent seismic hazard analysis, namely: the results of HVSR technique were accepted for low ($f < 1.0$ Hz) frequencies and the VHR data were used for higher frequencies. We did not take into consideration possible non-linear response of soil during strong excitation due to a lack of necessary information and data. The examples of the site amplification functions are shown in Figure 3.

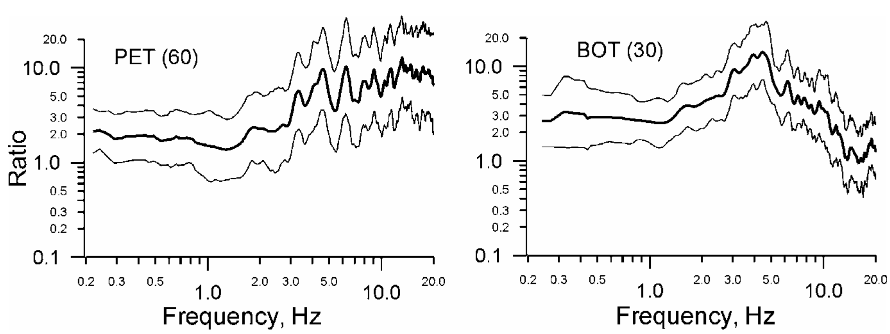

Figure 3. Examples of site amplification function (mean values and 1 standard deviation limits) for two soil sites - K2-stations: PET (epicentral area) and BOT (Bucharest). The numbers in parentheses show the number of used records.

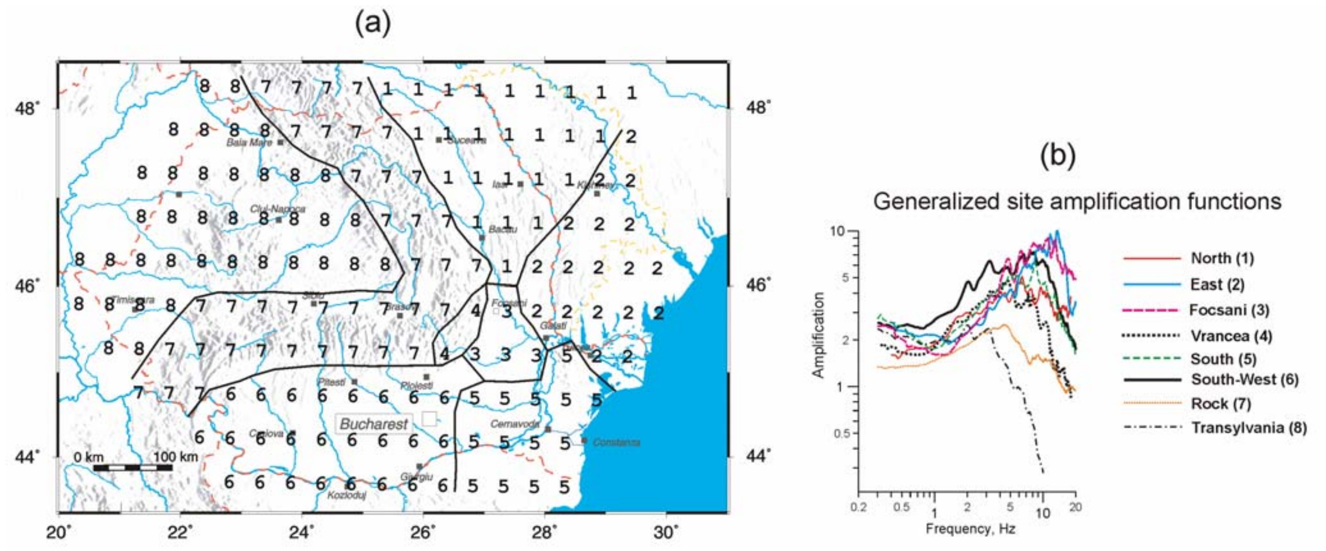

Figure 4. (a) Distribution of the generalized site amplification functions (regions) along the territory of Romania (see text for description of the numbers). (b) The generalized region-dependent site amplifications (mean amplitude values) including amplification for the "rock" category.

Besides the data from particular sites, we used combination of the data from the K2-network and 36 sites of the CALIXTO network for evaluation of generalized region-dependent site amplification. To consider the azimuth-dependent distribution of ground motion parameters from the Vrancea earthquakes, the territory of Romania was divided into 8 characteristic regions bearing in mind both azimuthal direction from the Vrancea zone and general geological and geomorphological conditions (Figure 4a) (see Sokolov et al., 2008, for detail). The generalized "region-dependent" amplification functions (Figure 4b) were evaluated by averaging of all data, which were obtained for stations located within the given region. These generalized functions were used together with developed source scaling and attenuation models for calculation of region-dependent spectra.

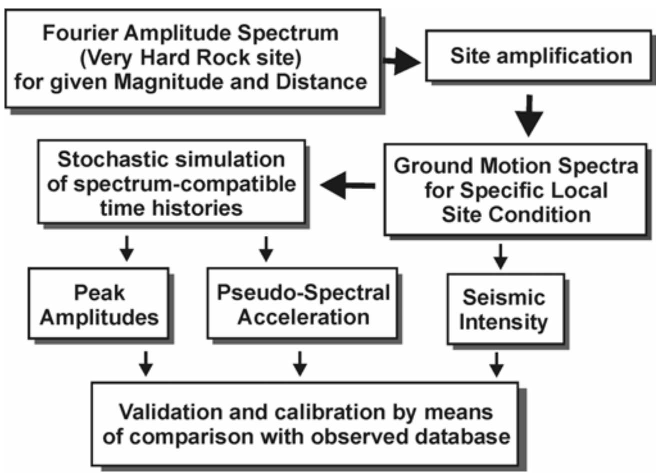

Figure 5. Scheme of evaluation of the ground-motion attenuation models based on the Fourier amplitude spectra.

The region-dependent spectra were used for development of ground motion prediction equations for Peak Ground Acceleration (PGA) and Velocity (PGV), Pseudo-Spectral Acceleration (PSA, 5% damping) at various frequencies, and seismic intensity (SI, MSK or MMI scale) as the functions of magnitude (M), depth (H, km), and epicentral distance (R, km) (Sokolov et al., 2008). The scheme of analysis is shown in Figure 5. After calculation of Fourier Amplitude spectra for a range of input characteristics (magnitudes, distances and depths), the sets of 40 synthetic acceleration time functions were generated using the spectra (Boore, 2003). The duration model, in which it is assumed that most (90%) of the spectral energy is spread over a duration $\tau_{0.9}$ of the accelerogram, was evaluated using available strong-motion data. Second, the PGA and PSA values were obtained as the average values from the acceleration time functions. Peak velocities (PGV) were evaluated from the integrated synthetic accelerograms after high-pass filtering with the cut-off frequency of 0.2 Hz. Seismic intensity (MSK scale) estimations were obtained directly from the FAS (Sokolov 2002).

Sokolov et al. (2008) developed the strong-motion models for eight regions covered the territory of Romania (Figure 4a). Peak amplitudes of ground acceleration, as well as amplitudes of pseudo-spectral acceleration (PSA), may be sensitive to the amplitudes of particular peaks of the frequency-dependent soil amplification function. The procedure of averaging of the site amplification functions, which was performed when developing the "region-dependent" amplification, leads to smoothing of the peaks. The use of mean-amplitude functions in predicting of the site-dependent PGA and PSA values may result in underestimation of the parameters. Therefore, when developing attenuation models, two variants of input data were used, namely: the mean and the mean + 1 standard deviation amplitudes of the empirical generalized site amplification. Recent studies by Sokolov et al. (2004ab, 2008) showed that, when considering these two variants of site amplification amplitudes, the most part of the observed data (PGA and response spectra) lay between the estimations. Thus, the application of one standard deviation of the empirical site amplification function would provide an estimation of the possible upper boundary of the values of ground motion parameter, e.g. maximum from two horizontal components, etc. Figure 6 shows examples of the attenuation curves.

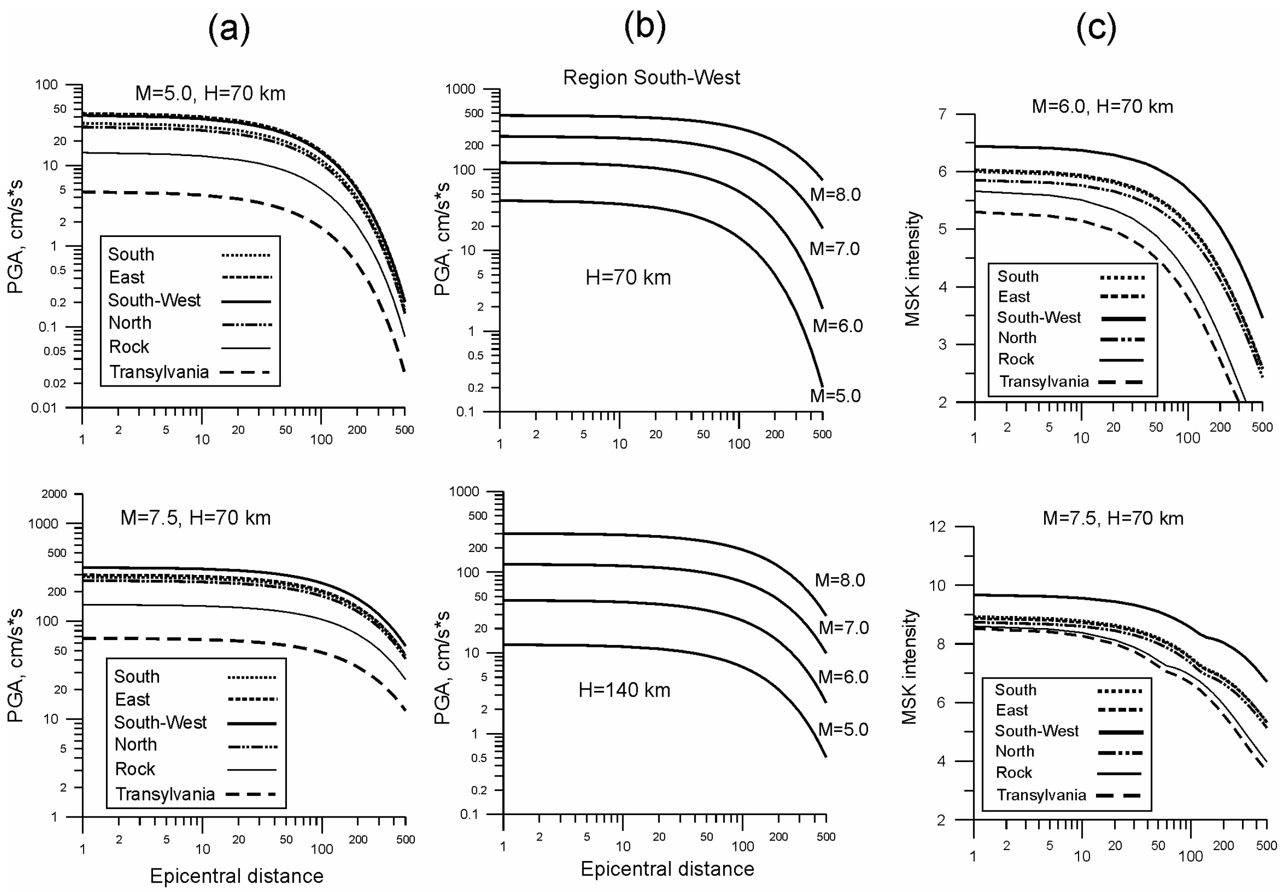

Figure 6. Examples of the attenuation curves developed for Romania (Sokolov et al., 2008). Comparison of the modelled PGA (a, b) and MSK intensity (c) curves for various zones, magnitudes (M), depth (H), and epicentral distances.

3. RESULTS

Our method for the ShakeMap generation uses region-specific (azimuth-dependent) attenuation relations determined from seismological information gathered during previous Vrancea earthquakes (Sokolov et al., 2008). The seismological approach, as presented here, it allowed incorporating any kinds of weak, moderate and strong motion observations of past earthquakes. These include in these case of Romania several weak motion observations, a few records of strong earthquakes (1986 and 1990), and intensity maps for four strong events (1944, 1977, 1986, and 1990). Note, that the spectral models, which were used here, do not contain detailed references to the surface geology in Romania. Nonetheless, they allow mimicking the patterns of peak values and intensities as observed during past strong Vrancea earthquakes.

For practical calculations we applied the following scheme. The territory was covered by a grid with 0.20^0 x 0.20^0 spacing and the index of correspondent characteristic region was assigned to every node of the grid (see Figure 4a). The boundaries of the regions are considered as the “soft” borders, i.e. the nodes located near the boundary may belong simultaneously for two, or even three, regions. The node-to-boundary distance in this case should be less than 50 km. The correspondent weights are assigned to the nodes and the weights depend on the distance between the nodes and the region borders. The smaller the distance to the border, the larger the weight of the neighbouring region. Initially, the ground motion parameters for the particular earthquake are calculated for the nodes. For the sites located between the nodes, a simple interpolation scheme based on the distances between the site and four neighbouring nodes is used.

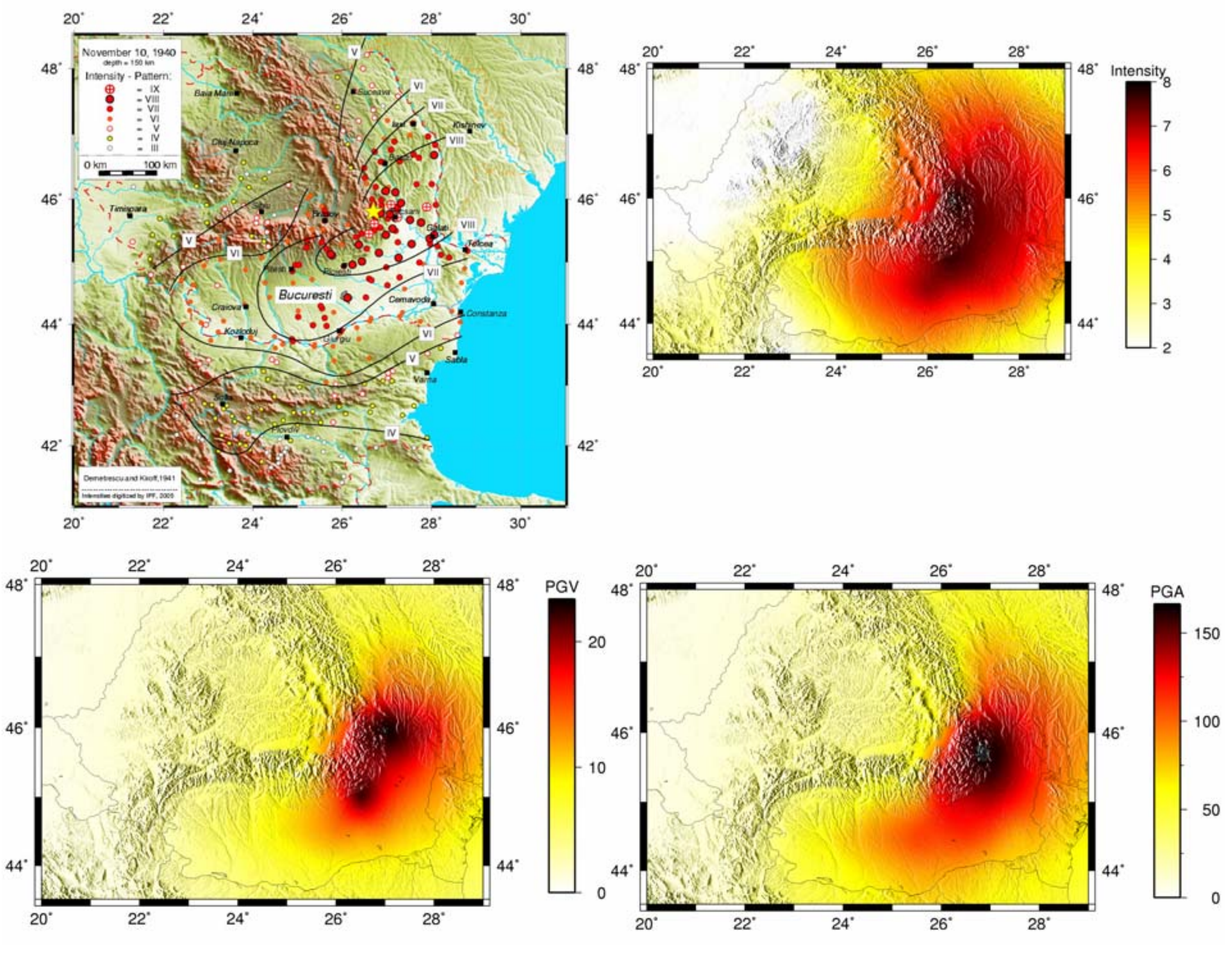

Figure 7. The observed macroseismic maps and the modelled distribution of ground motion parameters (MSK intensity, Peak Ground Acceleration and Peak Ground Velocity) for the earthquake of November 10, 1940 (M_W 7.7, depth 140 km).

Figures 7 and 8 show the modelled distribution of seismic intensity, peak ground acceleration and peak velocity along the Romanian territory during the earthquakes of March 4, 1977 (M_W 7.4, depth 95 km) and November 10, 1940 (M_W 7.7, depth 140 km). The instrumental data are not available for the events and only observed macroseismic maps are shown here for comparison. Note that the earthquake sources were described as the point sources and no specific peculiarities of the radiation pattern and the rupture propagation were considered.

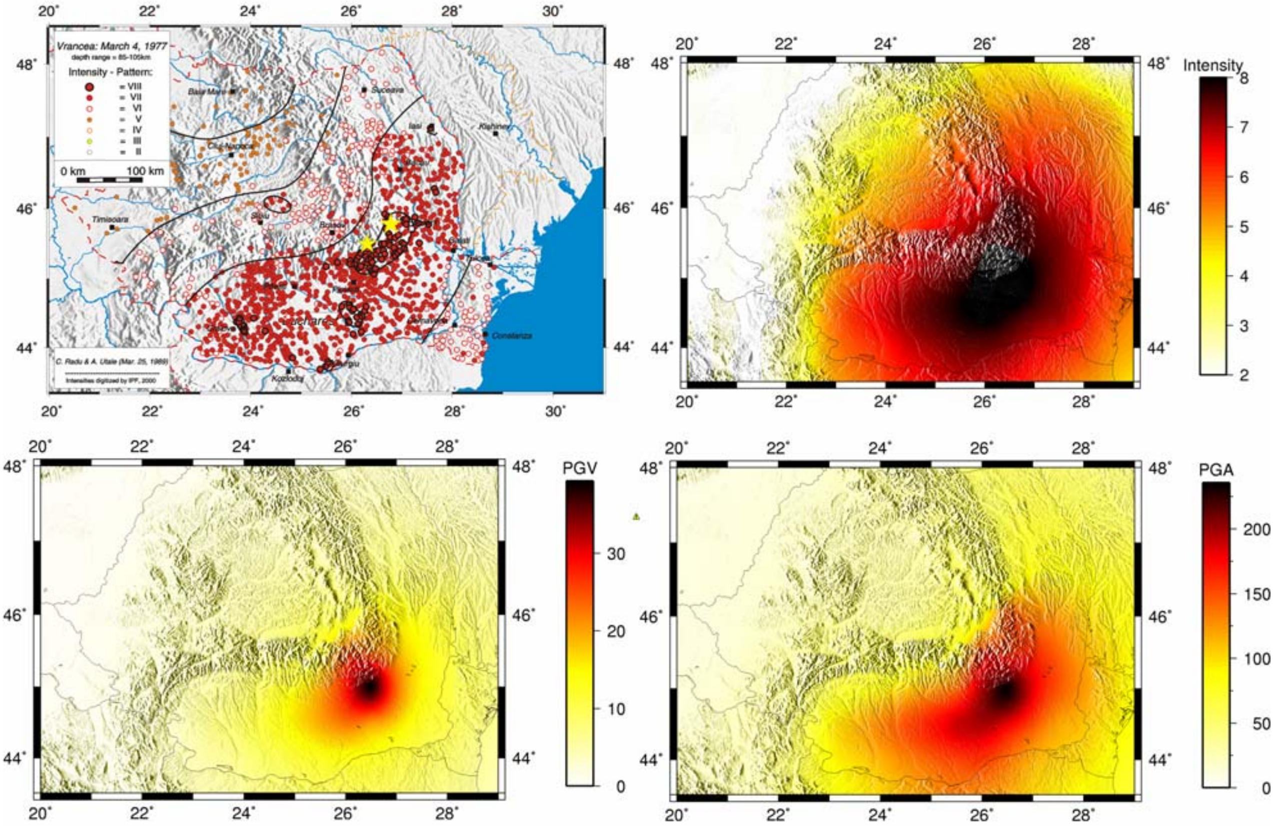

Figure 8. The observed macroseismic maps and the modelled distribution of ground motion parameters (MSK intensity, Peak Ground Acceleration and Peak Ground Velocity) for the earthquakes of March 4, 1977 (M_W 7.4, depth 95 km).

4. DISCUSSION AND CONCLUSION

The results of the modeling show that the applied technique, even if it is based on small amount of observed strong-motion data, reveals high ability to predict site-depending strong ground motion parameters. Besides macroseismic intensity and peak ground acceleration, the ShakeMap generation can be performed also in terms of peak ground velocity and response spectra. Because the technique uses Fourier amplitude spectrum as the main input parameter, it is easily possible to introduce site-specific coefficients that take into consideration frequency dependent influence geological, geomorphological, and geotechnical characteristics of the sediments.

As a matter of principle, attenuation relations used here predict the general features of ground motion, not peculiarities of special earthquakes. In many cases (and this is even more true shortly after strong earthquake, i.e. when shake maps are mostly required), detailed source parameters, in particular slip distributions are unknown. However, the procedure of ShakeMap generation implies the utilization of information from the seismic network (observed ground motion parameters). The ground motion models are used for so-called “phantom” sites that fill the space between the recording sites. Obviously, the reliability of the resulting schemes of ground motion distribution generated shortly after real earthquake would increase with density of strong-motion network. For future studies of shake maps in Romania we propose to include site-specific correction terms of the generalized amplification functions and empirical attenuation relations. Besides, in the case of very strong earthquake source finiteness needs to be taken into account.

REFERENCES

Bonjer, K.-P., Oncescu, L., Rizescu, M., Enescu, D., Driad, L., Radulian, M., Ionescu, V. and Moldoveanu, T. (2000). Source- and Site-Parameters of the April 28, 1999 Intermediate-Depth Vrancea Earthquake: First Results from the New K2-Network in Romania. *XXVII General Assembly of the European Seismological Commission*, Lisbon, Book of Abstracts and Papers, SSA-2-13-O, 53.

Boore, D.M. (2003). Simulation of Ground Motion Using the Stochastic Method, *Pure and Applied Geophysics*, **160**, 635-676.

Lermo, J. and Chavez-Garcia, F.J. (1993). Site Effect Evaluation Using Spectral Ratios with Only One Station, *Bulletin Seismological Society America*, **83**, 1574-1594.

Mandrescu, N., Anghel, M. and Smalberbergher, V. (1988). The Vrancea Intermediate-Depth Earthquakes and the Peculiarities of the Seismic Intensity Distribution over the Romanian Territory. *St. Cerc. Geofiz., Geogr., GEOFIZICA* **26**, 51-57.

Mandrescu, N. and Radulian, M. (1999). Macroseismic Field of the Romanian Intermediate-Depth Earthquakes, *Vrancea* Earthquakes*: Tectonics, Hazard and Risk Mitigation*, Wenzel, F., Lungu, D. and Novak, O. (Editors), Kluwer Academic Publishers, Dordrecht,163-174.

Martin, M., Wenzel, F. and the CALIXTO working group (2006). High-resolution teleseismic body wave tomography beneath SE-Romania – II. Imaging of a slab detachment scenario, *Geophys. J. Int.* **164,** 579–595.

Moldovan, I.-A., Enescu, B.D. and Ionescu, C. (2000), Predicting Peak Ground Horizontal Acceleration for Vrancea Large Earthquakes Using Attenuation Relations for Moderate Shocks, *Romanian Journal of Physics* **45** (9-10), 785-800.

Oncescu, M.-C., Bonjer, K.-P. and Rizescu, M. (1999). Weak and Strong Ground Motion of Intermediate Depth Earthquakes from the Vrancea Region. F. Wenzel et al. (eds), *Vrancea earthquakes: tectonics, hazard and risk mitigation*, Kluwer Academic Publishers, Dordrecht, 27-42.

Radu, C., Polonic, G. and Apopei, I. (1979). Macroseismic Field of the March 4, 1977 Vrancea Earthquake. *St. Cerc. Geofiz., Geogr., GEOFIZICA*, **23**, 19-26.

Radulian, M., Mandrescu, N., Panza. G.F., Popescu, E. and Utale, A. (2000). Characterisation of Seismogenic Zones of Romania, *Pure and Applied Geophysics* **157**, 57-77.

Sokolov, V. (2002). Seismic Intensity and Fourier Acceleration Spectra: Revised Relationship, *Earthquake Spectra* **18**, 161-187.

Sokolov, V., Bonjer, K-P. and Rizescu, M. (2004a). Site Effect Evaluation Using Different Techniques: a Case of Intermediate Depth Vrancea (Romania) Earthquakes, *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver, Canada, August 1-6, 2004, Paper No. 3230

Sokolov, V., Bonjer, K.-P. and Wenzel, F. (2004b). Accounting for Site Effect in Probabilistic Assessment of Seismic Hazard for Romania and Bucharest: a Case of Deep Seismicity in Vrancea zone, *Soil Dynamics and Earthquake Engineering*, **24:12**, 927-947.

Sokolov, V., Bonjer, K-P., Oncescu, M, and Rizescu, M. (2005), Hard Rock Spectral Models for Intermediate-Depth Vrancea (Romania) Earthquakes, *Bulletin Seismological Society America* **95**, 1749-1765.

Sokolov, V., Bonjer, K.-P., Wenzel, F., Grecu, B. and Radulian, M. (2008). Ground-motion prediction equations for the intermediate-depth Vrancea (Romania) earthquakes, *Bulletin of Earthquake Engineering*, doi:10.1007/s10518-008-9065-6.