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ORIGINAL RESEARCH PAPER

Ground-motion prediction equations for the intermediate depth Vrancea (Romania) earthquakes

Vladimir Sokolov · Klaus-Peter Bonjer · Friedemann Wenzel · Bogdan Grecu · Mircea Radulian

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Abstract We present the regional ground-motion prediction equations for peak ground acceleration (PGA), peak ground velocity (PGV), pseudo-spectral acceleration (PSA), and seismic intensity (MSK scale) for the Vrancea intermediate depth earthquakes (SE-Carpathians) and territory of Romania. The prediction equations were constructed using the stochastic technique on the basis of the regional Fourier amplitude spectrum (FAS) source scaling and attenuation models and the generalised site amplification functions. Values of considered ground motion parameters are given as the functions of earthquake magnitude, depth and epicentral distance. The developed ground-motion models were tested and calibrated using the available data from the large Vrancea earthquakes. We suggest to use the presented equations for the rapid estimation of seismic effect after strong earthquakes (Shakemap generation) and seismic hazard assessment, both deterministic and probabilistic approaches.

Keywords Vrancea region · Strong ground motion · Prediction equations

V. Sokolov (✉) · K.-P. Bonjer · F. Wenzel
Geophysical Institute, Karlsruhe University, Hertzstr.16, Karlsruhe, Germany
e-mail: Vladimir.Sokolov@gpi.uni-karlsruhe.de

K.-P. Bonjer
e-mail: Klaus.Bonjer@gpi.uni-karlsruhe.de

F. Wenzel
e-mail: Friedemann.Wenzel@gpi.uni-karlsruhe.de

B. Grecu · M. Radulian
National Institute for Earth Physics, PO Box MG-2, Bucharest-Magurele, Romania
e-mail: bgrecu@infp.ro

M. Radulian
e-mail: mircea@infp.ro

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 Carpathians Arc in Romania. The region is characterized by a high rate of occurrence of large earthquakes in a narrow focal

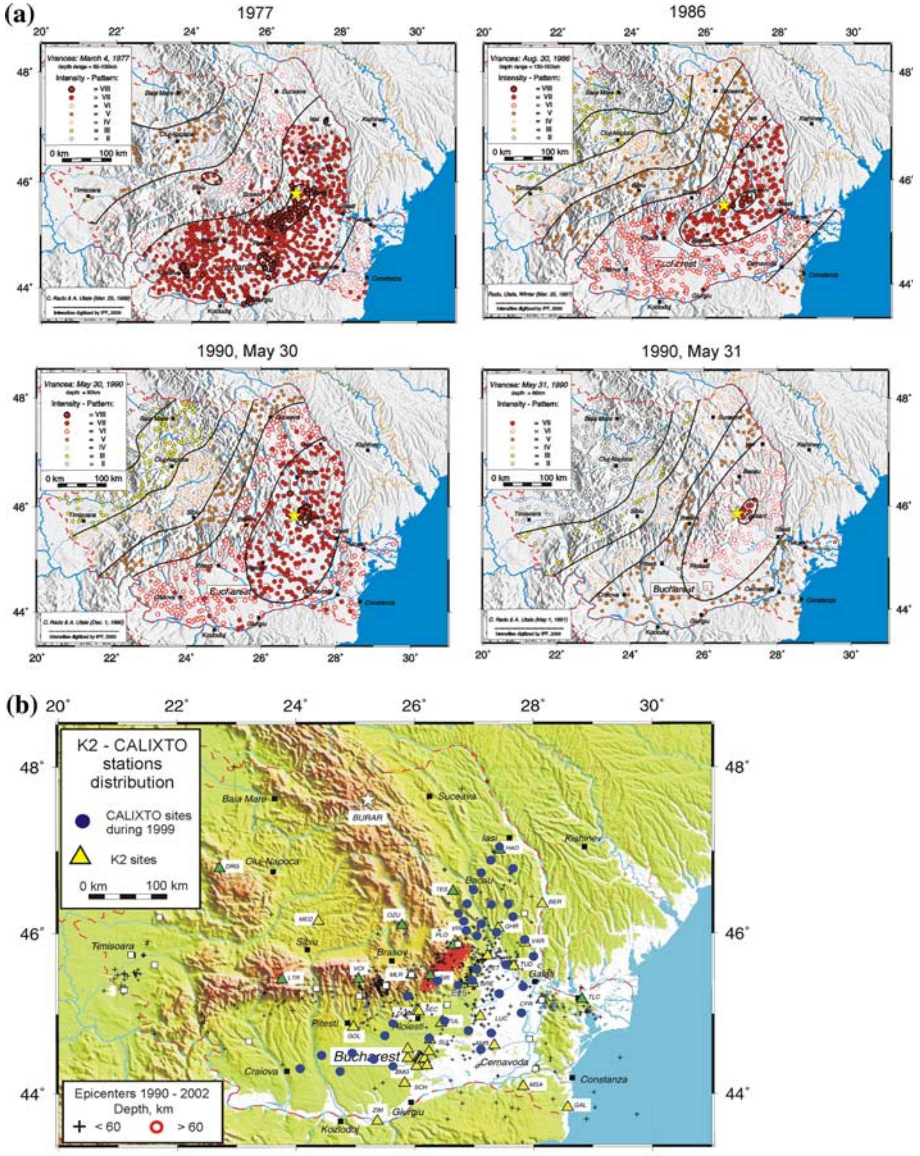

Fig. 1 The Vrancea seismicity. (**a**) Observed distribution of macroseismic intensity during the large Vrancea earthquakes. (**b**) Epicentral map of the Vrancea earthquakes (1990–2002), and location of the seismic networks, records from which were used in this study

Table 1 Parameters of the large Vrancea earthquakes, the data from which are used in this study

Date	Epicenter	Depth (km)	Moment magnitude
10 November, 1940	45.8 N, 26.7 E	140	7.7
4 March, 1977	45.77 N, 26.49 E	95	7.4
30 August 1986	45.52 N, 26.49 E	130	7.2
30 May 1990	45.83 N, 26.89 E	90	6.9
31 May 1990	45.85 N, 26.91 E	85	6.3

zone. The epicentral zone is confined to about 60 × 20 sq. km and the seismic activity ranges within an almost vertical stripe in depths between 70 and 170 km. During the last century four major Vrancea earthquakes occurred in the zone (Fig. 1, Table 1). The former two lead to disastrous impact on Romanian territory. For example, in the March 4, 1977 event, 1,570 people died, 11,300 were injured and 32,500 residential and 763 industrial units were destroyed or were seriously damaged (Sandi 2001).

Analysis of the macroseismic (Fig. 1a) and instrumental data from the intermediate-depth Vrancea earthquakes revealed several peculiarities of the earthquake effects (e.g. Ivan et al. 1998; Mandrescu and Radulian 1999; Mandrescu et al. 1988). They may be summarized as follows:

- The earthquakes affect very large areas with a predominant NE-SW orientation;
- The local and regional geological conditions can control the amplitudes of earthquake ground motion to a larger degree than magnitude or distance. The strong ground motion parameters exhibit a large variability depending on site location.

The relationships between ground motion parameters and earthquake characteristics in the Vrancea zone are represented by the empirical azimuth-dependent attenuation equations for seismic intensity (e.g. Ivan et al. 1998; Marza 1996; Marza and Pantea 1994) and maximum peak ground acceleration (Lungu et al. 1995, 1997). The studies were based on the macroseismic data and the analog accelerograms of the strong Vrancea earthquakes of 1977, 1986 and 1990.

In this work we made an attempt to develop the regional ground-motion prediction equations for peak ground acceleration (PGA), peak ground velocity (PGV), pseudo-spectral acceleration (PSA), and seismic intensity (MSK or MMI scale) for the Vrancea intermediate-depth earthquakes and territory of Romania. The Fourier amplitude spectrum (FAS) source scaling and attenuation models (Sokolov et al. 2005) and the generalised site amplification functions were used for the purpose. The stochastic technique (Boore 2003) based on the site-dependent spectra was used for the case of PGA, PGV, and PSA models. The equations for seismic intensity were evaluated using the recently developed relations between intensity and FAS (Chernov and Sokolov 1999; Sokolov 2002). The values of the considered ground motion parameters are given as functions of magnitude (M_W 5 − 8), depth (70–160 km), and epicentral distance (up to 500 km). The maximum magnitude for the Vrancea zone was accepted to be M = 8 after Lungu et al. (1999), and Marza et al. (1991).

2 Input data

The 1977 earthquake was recorded in Romania by only one accelerograph located in Bucharest. The other strong events of 1986 and 1990 (M_W 7.1, 6.9, and 6.3) produced more

Table 2 Seismological parameters of the VHR spectral model for the Vrancea earthquakes

Parameter[a]	Description
Fourier acceleration spectrum A(f)	$A(f) = (2\pi f)^2 CS(f)D(R, f)$
The scaling factor C	$C \sim 1/(4\pi\rho\beta^3 R)$
Source spectrum $S(f)$	Brune (1970) ω-square, point source $S(f) = M_0/\left[1 + (f/f_0)^2\right]$
Corner frequency f_0	$f_0 = 4.9 \times 10^6 \beta(\Delta\sigma/M_0)^{1/3}$
Stress parameter $\Delta\sigma$ (bar)	Increase from 200 bars for M = 5 to 1000 bars for M = 7.5
Density, ρ (gm/cm^3)	2.8
Shear velocity, β (km/s)	3.8
Frequency-dependent attenuation $D(R, f)$	$D(R, f) = \exp[-\pi f R/Q(f)\beta]P(f, f_{max})$
Path attenuation $Q(f)$	$150 f^{0.8}$ (H 100–200 km); $400 f^{0.8}$ (H 100–40 km); $100 f^{0.8}$ (H<40 km) (Radulian et al. 2000)
High-frequency filter $P(f)$	$P(f) = exp(-\pi\kappa f)$ (Anderson and Hough 1984)
Site attenuation, κ (s)	$\kappa = 0.01$ M

[a] f is the frequency, Hz; R is the source-to-site (hypocentral) distance, km; M_0 is the seismic moment

than 30 free-field records each. Small and moderate size Vrancea earthquakes ($M_W < 6.0$) were recorded by the K2 accelerometer network (Fig. 1b), 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 (Bonjer et al. 2000). Several hundred records of small earthquakes were also obtained in 1999 by a temporary network during the CALIXTO (Carpathian Arc Lithospheric X-Tomography) experiment (http://www-sfb461.physik.uni-karlsruhe.de/pub/A2/a2_res_en.html). The local site conditions vary from metamorphic rock to thick and water-saturated sedimentary formation (Sokolov et al. 2004a).

The parameters of the regional FAS model are summarized in Table 2 (see also Sokolov et al. 2005). For description of site response we used site-specific amplification functions, which were evaluated for particular stations of the K2 and the CALIXTO networks (Sokolov et al. 2004a,b; Sokolov et al. 2005; Sokolov and Wenzel 2007). The amplification functions were estimated within frequency range from 0.3–0.5 Hz to 12–15 Hz using two so-called "non-reference" techniques. One of the techniques is a modification of the well-known horizontal-to-vertical Fourier spectral ratio (H/V technique) of the S-wave phase, which was proposed for earthquake ground motion by Lermo and Chavez-Garcia (1993). The second one (Sokolov et al. 2000) consists in calculating ratios between the spectra of actual earthquake records (horizontal components) and those modelled for a hypothetical very hard rock site (VHR ratio technique). The modelled spectra are calculated using the regional source scaling and attenuation model and the parameters of the actual earthquake.

The H/V technique, as has been shown recently by many authors, provides results that are consistent with the general geological conditions of the recording sites. The results of the application of the H/V technique, however, are affected by local and subsurface factors influencing the vertical component of ground motion. The VHR approach, in turn, does not completely eliminate the effects of source rupture peculiarities and inhomogeneous propagation path and it is sensitive to the low-frequency noise.

In this study, we used a combined variant for the frequency-dependent site amplification, namely: the results of the H/V technique were accepted for low ($f < 1.0$ Hz) frequencies and the VHR ratio data were used for higher frequencies. We do not take into consideration possible non-linear response of the soil during strong excitation due to a lack of necessary information and data.

Initially we divided the area that is covered by ground motion networks into six characteristic regions (Fig. 2a), bearing in mind both general geological and geomorphological conditions and azimuthal direction from the Vrancea zone. The characteristics of the region-dependent site amplification were evaluated by averaging of all data, which were obtained for stations located within the given region. We also introduced two additional characteristic regions to cover the whole territory of Romania, namely: “Mountain” and “Transylvania”. The generalised amplification for the rock model used for the region “Mountain” (or “Rock”) was taken from our recent study (Sokolov et al. 2005). The region of the Transylvanian basin, which is situated toward North-West from the Vrancea area, is characterized by anomalous attenuation of seismic waves (Radulian et al. 2006). The seismic effect from the Vrancea earthquakes in the Transylvanian basin is much lower than in the other territory of Romania for the same distances. The amount of available earthquake records for the region is insufficient for site response analysis. Thus, following conclusions made by Radulian et al. (2006), we constructed an “artificial” function for the case applying additional filter, which substantially reduce level of the high-frequency radiation. The mean amplitude values of the generalised amplification functions are shown in Fig. 2b. The accepted distribution of the characteristic regions which cover the whole Romanian territory is shown in Fig. 2c. The labeling is as following: 1—region “North”; 2—region “East”; 3—region “Focsani”; 4—region “Vrancea”; 5—region “South”; 6—region “South-West”; 7—region “Mountain” or “Rock”; 8—region “Transylvania”. The description of geological conditions and generalised soil classes based on NEHRP classification assigned to the characteristic regions is given in Table 3.

The amplification characteristics may vary significantly from one region to another depending on the frequency range. The regions “East” and “Focsani” are characterized by the highest amplification in the high frequency (>10 Hz) range, while the region “South-West” exhibits the relatively high amplification for the intermediate frequencies (1–4 Hz). The regions “North” and “South” show almost the same amplification for frequencies more than 1 Hz. The increase of amplification amplitudes toward the lower frequencies (region “South-West”) may be explained by the influence of surface waves generated within the deep sediments of the Moesian platform.

Obviously the assigned site classification should be considered as rough definition. The regions with the same characteristic site classes (for example, the regions “South” and “South-West”) may reveal significant differences in the generalised amplification functions due to the regional peculiarities. We provided this gross definition for possible application of the additional site-specific coefficients that may be available in future.

3 Regression analysis

The region-dependent ground motion prediction equations were developed 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). The scheme of analysis is shown in Fig. 3. First, the site-dependent Fourier amplitude spectra (FAS) were evaluated using the spectral source scaling and attenuation models and the generalised regional amplification functions for a range of input characteristics (magnitudes, distances and depths). Second, the sets of 40 synthetic acceleration time functions were generated using the spectra.

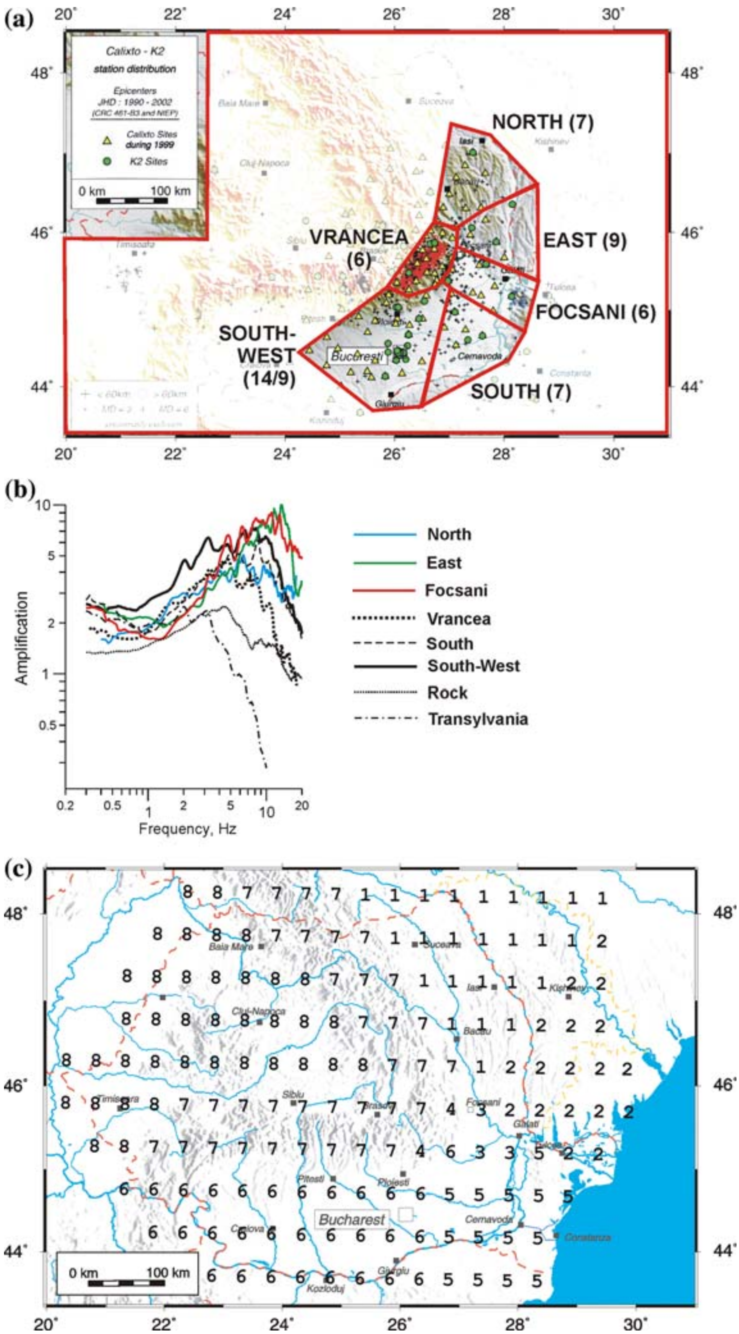

Fig. 2 Evaluation of the generalised site amplification. (**a**) Scheme of the characteristic regions and location of K2 and CALIXTO stations. Numbers in parentheses denote number of the stations within the region. For the South-West region, the numbers also show the number of stations (9) in the city of Bucharest. (**b**) The generalised region-dependent site amplifications (mean amplitude values) including amplification for the generalised "rock" category. (**c**) Distribution of the generalised site amplification functions (regions) along the territory of Romania (see text for description of the numbers)

Table 3 Geological description of the characteristic regions

Characteristic region	Geological description
"North"	Pre-Quaternary (Miocene) stiff rock and stiff soil, NEHRP soil class CD. The narrow river valleys are filled by shallow fluviatile (loess and loess-like) deposits, NEHRP class DE
"East"	Pre-Quaternary (Pliocene) and Quaternary (Pleistocene) deposits, NEHRP soil class CD
"Focsani"	Thick Pre-Quaternary and Quaternary sediments and recent alluvium (up to 2000 m), NEHRP soil class D
"Vrancea", "Rock"	Precenozoic (cretaceous) and early cenozoic rocks, NEHRP soil class BC.
"South"	Quaternary deposits, thickness 100 m–300 m, NEHRP soil class DE
"South-West"	Thick Quaternary deposits of Moesian Platform, thickness more than 250–300 m, NEHRP soil class DE
"Transylvania"	Miocene and Pliocene deposits, NEHRP soil class CD

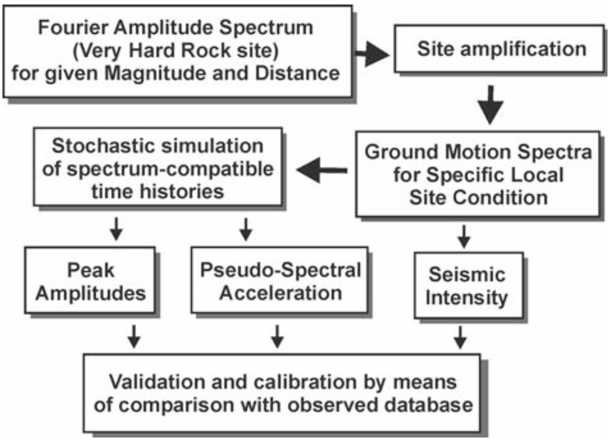

Fig. 3 Scheme of evaluation of the ground-motion attenuation relationships based on the Fourier amplitude spectra

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 (Sokolov et al. 2004a). In this study we used a distance-independent duration model, however for rock sites the value of duration was reduced by 20%. Third, 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. Such filtering is a standard procedure when processing the empirical strong ground motion records. Seismic intensity (MSK scale) estimations were obtained directly from the FAS (Sokolov 2002).

Peak amplitudes of ground acceleration, as well as pseudo-spectral acceleration, may be sensitive to the amplitudes of the particular peaks of frequency-dependent soil amplification function. The procedure of averaging of the site amplification functions leads to smoothing of the peaks. The use of the mean-amplitude amplification in predicting of the site-dependent PGA and PSA values may result in underestimation of the parameters. Therefore, when considering the site effects, we used two variants, namely: (1) the mean and (2) the mean + 1 standard deviation amplitudes of the empirical site amplification. The mean values were calculated assuming log-normal distribution of the amplitudes of amplification. The variants will be further mentioned as AM and AM1, correspondingly. It has been shown recently (Sokolov et al. 2004a,b) that the use of the AM1 model provides a reasonable estimation of the upper boundary of PGA values.

The example of distribution of the modelled ground motion parameters versus epicentral distance R for fixed magnitudes M and depths H is shown in Fig. 4. The parameters are considered as the geometric mean values of the mutually perpendicular horizontal components. The obtained datasets were used for the regression analysis. The ordinary least squares (OLS) technique was used testing the different combinations and representation (normal or logarithmic) of the independent variables M, H, R, or hypocentral distance D. The following equation produces the smallest residual and the largest R-square coefficient almost in all cases.

$$\ln Y = a + b \ln M + c \ln D + dD \tag{1}$$

where Y is the ground motion parameter. The comparison between the modelled PGA and the relationships estimated using the equation for the South-West area is shown on Fig. 4. Fitting quite well with the modelled data for large magnitudes, the equation however resulted in the higher, than the modelled, values for small magnitudes. Also the equation is characterized by unusually rapid attenuation with distance for large focal depths.

When analyzing distribution of the modelled data versus epicentral distance for particular magnitudes and depths, it can be seen (Fig. 4) that the approximation of the data in a simple form $\ln Y = a + bR$ seems to be appropriate for all ground motion parameters. Analysis of the sets of the equations for all considered magnitudes and depths shows that the coefficients a and b are the magnitude- and depth-dependent quantities. The OLS analysis of the dependence resulted in the following equations for PGA (cm/s^2), PGV (cm/s), and PSA (cm/s^2) at given frequency

$$\ln Y = a_1 + a_2 \ln M - \exp(a_3 + a_4 \ln H)R + a_5 H \tag{2}$$

and for MSK intensity

$$\ln Y = a_1 + (a_2 + a_3 H) \ln M + (a_4 + a_5 \ln H)R + a_6 H \tag{3}$$

where M is the moment magnitude; R is the epicentral distance, km; H is the focal depth, km. The equations appear to be unusual, as they use the "ln M" term instead of the common "M" term. However, despite of their unusual form, the equations provide a very good fit with the modelled data for all considered magnitudes and focal depths. The coefficients $a_1 - a_6$ were evaluated separately for every considered region.

For the case of peak amplitudes and pseudo-spectral acceleration, we can not estimate the standard error term in our models based on comparison between the modelled and observed data due to a lack of the observed data. Therefore we suggest using two variants of the site amplification—the AM and AM1 models. The difference between the results of application of the models, or the ratio between the "normal" (AM variant) and the "conservative" (AM1 variant), depends on the relationship between the envelopes (or frequency content) of the VHR spectra and the generalized site amplification functions. For example, the ratio may vary from 1.1 to 0.7 log units for the PGA estimations when considering the regions "East" and "South-West" correspondingly. The error term for MSK intensity will be stated in the following section.

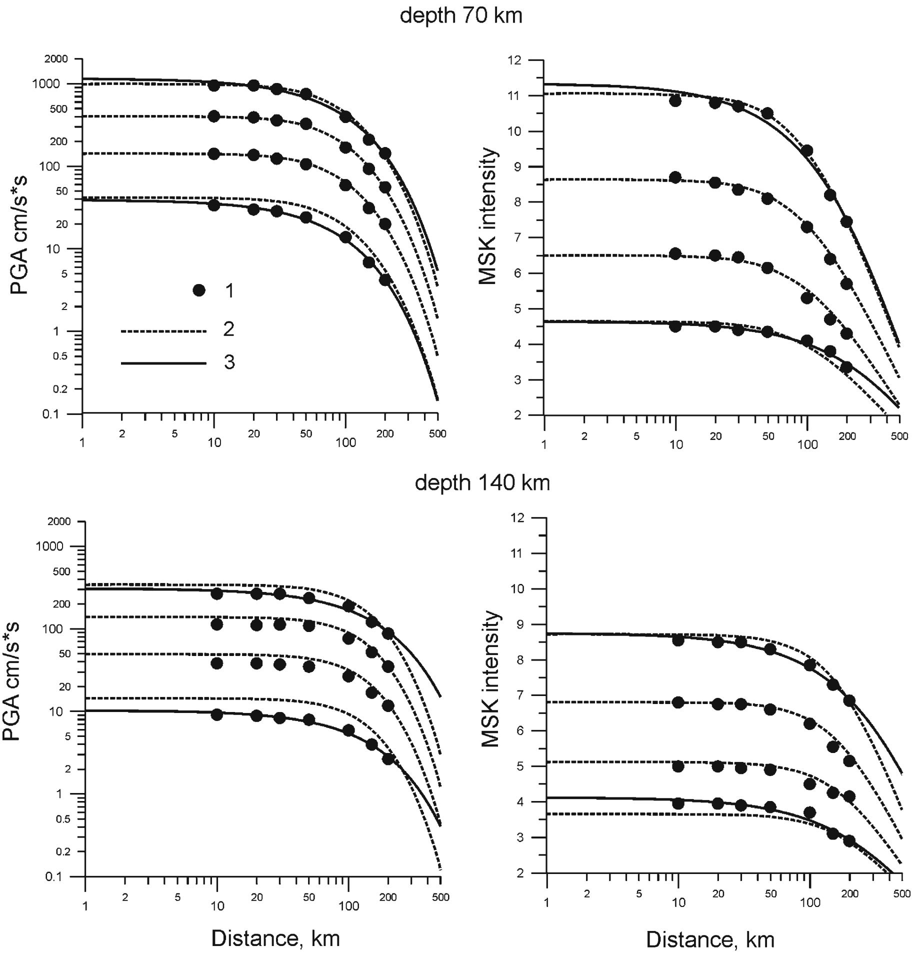

Fig. 4 Regression analysis of the modelled values shown as the black circles (1). Dashed lines (2) show the regression based on hypocentral distance (Eq. 1). Solid lines (3) denote the fitting based on epicentral distance R as $\ln Y = a + bR$, where Y is the ground motion parameter

4 Validation and calibration of the relationships

The obtained prediction equations were tested using the empirical database, which contains a set of macroseismic data from the large Vrancea earthquakes (the events of 1977, 1986 and 1990) and recordings of ground acceleration obtained during the 1986 and the 1990 earthquakes.

4.1 Macroseismic intensity

When analysing the macroseismic data, it has been found that our seismic intensity equations underestimate the intensity values for large epicentral distances (more than 200–300 km) and relatively shallow (depth less 100 km) large earthquakes ($M > 6.5$) (Fig. 5a). The difference may reflect the influence of surface waves, which is not considered in our spectral models.

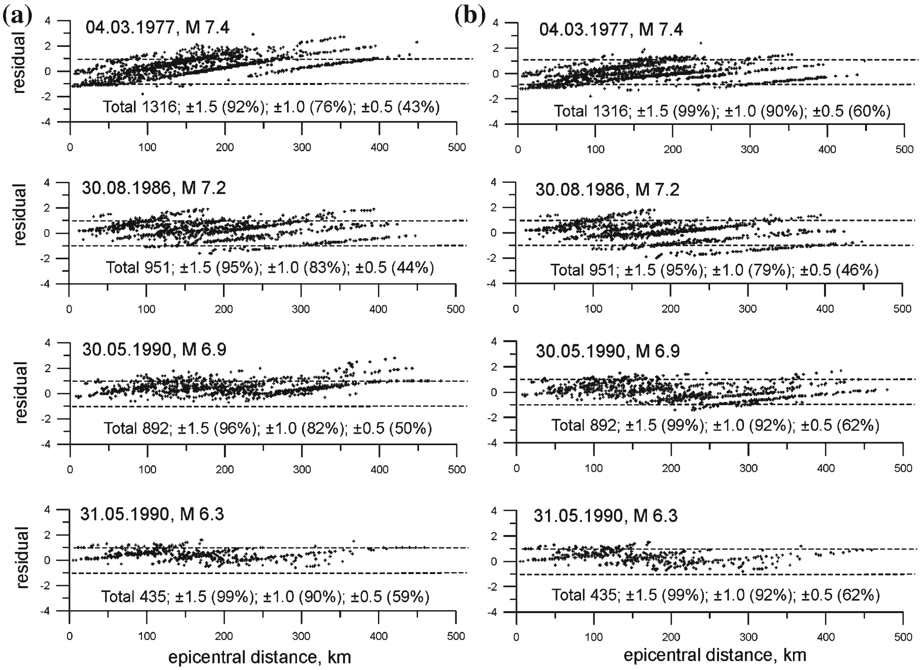

Fig. 5 Calibration of the intensity equations. The plots show residuals evaluated as difference between the observed intensity and the modelled values, which were calculated for large Vrancea earthquakes (**a**) using Eq. 3 and (**b**) after correction of the model using Eqs. 4a,b,c. Dashed lines show the limits of ±1 MSK unit. The plots show also the total number of macroseismic observations (MSK>II), and numbers of observations (percentage regarding the total number), for which the difference ΔI between the observed I_O and the modelled I_M values does not increase ±1.5, ±1.0 and ±0.5 units of macroseismic scale

A simple OLS analysis of the residuals ΔI between the observed I_O and the modelled I_M, which were calculated as $\Delta I = I_O - I_M$, allows introducing an additional empirical function for the distant-dependent modification of the modelled intensity $\Delta I_{R.}$ as follows

$$\Delta I_R = b_1 + b_2 \ln R, \tag{4}$$

where R is the epicentral distance, km; $b_1 = -5.11867$ and $b_2 = 1.264517$ for the regions “Rock” and “Transylvania”; $b_1 = -7.25714$ and $b_2 = 1.493281$ for the other regions. We also suppose that the ability of the Vrancea earthquakes to generate the surface waves decreases with the decrease of magnitude (M) and the increase of depth (H). The magnitude-dependent correction factor ΔI_M increases from the minimum value (0.0) for M_{MIN} up to the maximum value (1.0) for M_{MAX} as

$$\Delta I_M = \frac{M - M_{\text{MIN}}}{M_{\text{MAX}} - M_{\text{MIN}}}, \tag{4a}$$

The depth-dependent correction factor ΔI_H decreases from the maximum value (1.0) for the smallest depth (H_{MIN}) accepted for the Vrancea zone to the minimum value (0.0) for the largest depth (H_{MAX}) as follows

$$\Delta I_H = 1.0 - \frac{H - H_{\text{MIN}}}{H_{\text{MAX}} - H_{\text{MIN}}} \tag{4b}$$

The final correction is applied as

$$I_C = I_M + \Delta I, \quad \Delta I = \Delta I_R \times \Delta I_M \times \Delta I_H \tag{4c}$$

where I_C is the corrected value of the modelled intensity I_M. The correction is applied only for those distances, for which the value ΔI_R is more than zero.

The difference between the observed intensity and the corrected modelled values is shown in Fig. 5b. The following parameters of the correction were used, namely: $M_{MIN} = 6.0$, $M_{MAX} = 8.0$, $H_{MIN} = 70$ km, $H_{MAX} = 160$ km. The number of the particular macroseismic observations, for which the difference between the observed and the modelled values (ΔI) lays outside ±1.5, ±1.0 and ±0.5 MSK units, becomes smaller after the correction. The comparison allows estimating the value of standard error in Eq. 3 as 0.5 MSK units.

Note that the apparent linear trends in the residuals after correction are caused by an inherent characteristic of comparison between the modelled and the observed intensities. The observed intensities I_O are estimated as *integer* numbers while the modelled intensities I_M are given as the *decimal* estimations. For example, the intensity MSK VII (integer) may correspond to the modelled values varying between 6.5 and 7.5 (decimal). Thus, while the modelled values slightly decrease with distance within the limits of 1.0 MSK units, the observed intensities may remain the same causing the changing (from −0.5 to 0.5) residuals.

The developed equations can predict only the generalised features of distribution of seismic intensity. Every particular earthquake may reveal some peculiarities caused by the process of the earthquake source development. The relatively low level of intensity toward the northern direction from the epicentral area for the 1986 earthquake (distances 200–370 km) may be considered as the example of the peculiarities.

4.2 Peak amplitudes of ground acceleration (PGA)

The ground motion database used in this paper contains only one record of the earthquake of 1977; thirty one records of the earthquake of 1986; forty three records of the earthquake of 1990, May 30; and fourteen records of the earthquake of 1990, May 31. We made an attempt to increase the empirical database using the available relationships between macroseismic intensity and PGA proposed by Enescu (1997) and Bonjer et al. (2001) as follows

$$\log a_{\max} = 0.2712I + 0.1814 \quad V < I < \text{ IX after Enescu (1997)} \tag{5a}$$

$$\log a_{\max} = 0.29I + 0.14 \quad \text{after Bonjer et al. (2001)} \tag{5b}$$

where $a_{\max}$ is the maximum value from two horizontal components.

Based on these relationships, we created the two-component data for our analysis as follows. First, the intensity-based amplitude a_{IN} is estimated for every particular intensity observation that is more than MSK III as the geometric mean of two values calculated using the relationships 5a and 5b. Second, the a_{MAX} value was calculated as the random variable assuming log-normal distribution of the peak amplitudes with the mean value a_{IN} and standard deviation of 0.2 log units. Third, the value for the second component was evaluated as the random variable assuming uniform distribution between a_{MAX} and $0.7a_{MAX}$. The peak acceleration recalculated from the observed intensity values is called further as the "empirical" acceleration.

The difference between the empirical A_E and the modelled A_M peak amplitudes (AM variant) of ground acceleration was described as the residuals $\Delta A = \ln(A_E/A_M)$. Figure 6a shows distribution of the residuals, both for the recorded and "empirical" peak amplitudes, versus distance for the considered large earthquakes. The relatively shallow earthquakes (the

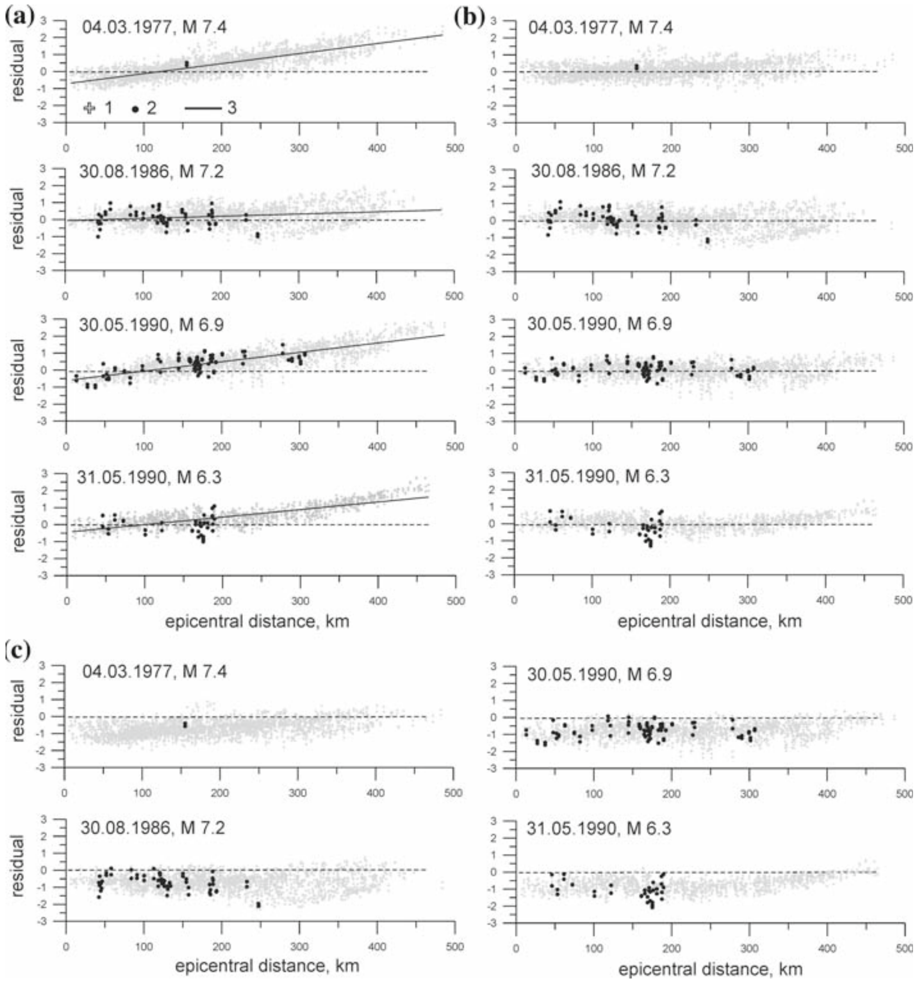

Fig. 6 Calibration of the PGA equations. The plots show the difference (residuals) between the observed (circles) and "empirical" (gray crosses, see text) PGA values (A_O) and the modelled data (A_M) calculated as $\Delta A = \log_{10}(A_O/A_M)$. The residuals were estimated using (**a**) Eq. 2, the AM variant (see text); (**b**) the AM variant, after correction of the model using Eqs. 5–5b; (**c**) the AM1 variant, after correction of the model using Eqs. 5–5b

events of 1977 and 1990, depth less 100 km) reveal the same phenomenon. First, the modelled PGAs are higher than the recorded and the "empirical" amplitudes for small epicentral distances (<50 km). Second, the modelled PGAs become smaller than the recorded and the "empirical" amplitudes with the increase of epicentral distance. In contrast, the deeper event (depth 130 km, 1986) reveals a good agreement between the considered data up to distances 300 km.

The disagreement between the peak acceleration values may reflect peculiarities of the propagation path, which do not considered in details in our attenuation models. The topmost part of the crust may be characterized by a higher attenuation of the high-frequency radiation than that provided in the model. The additional high-frequency attenuation due to nonlinear effects, the influence of which depends on earthquake depth and magnitude, should not be neglected. It seems also that the simple model for geometric attenuation (Table 2) leads to underestimation of the peak amplitudes at large epicentral distances.

A simple correction factor was evaluated from the residuals distribution using the OLS technique. The correction resulted in a good fit between the peak amplitudes of ground acceleration (Fig. 6b). The amplitudes, which were calculated using Eq. 2 for magnitudes more than a specified boundary magnitude M_{BND}, are corrected as

$$A_C = A_M \times \exp(\Delta A) \tag{6}$$

where A_C is the corrected acceleration; A_M is the modelled acceleration. The correction factor ΔA depends on epicentral distance and depth. The distant-dependent correction is calculated as

$$\Delta A_R = pR + q; \quad p = 0.0031M - 0.0163; \quad q = -0.3767M + 2.014 \tag{6a}$$

where M is the earthquake magnitude ($M > M_{BND}$); R is the epicentral distance, km. We assume that the correction is a depth-dependent quantity and it gradually decreases from the maximum value (1.0) for the smallest depth (H_{MIN}) accepted for the Vrancea zone to the minimum value (0.0) for the largest depth (H_{MAX}) as follows

$$\Delta A_H = 1.0 - \frac{H - H_{\mathrm{MIN}}}{H_{\mathrm{MAX}} - H_{\mathrm{MIN}}} \tag{6b}$$

where H is the earthquake depth. We introduced the same correction coefficients for all considered characteristic zones. The final correction is applied as $\Delta A = \Delta A_R \times \Delta A_H$.

We suppose that the correction is a frequency-dependent quantity and we do not suggest applying these equations for peak ground velocity. The attenuation of the high-frequency radiation, which leads to the decrease of acceleration amplitudes, should not cause the same effect for the case of velocity due to the different frequency ranges that are responsible for acceleration and velocity amplitudes. For pseudo-spectral acceleration we suggest the following scheme. The correction calculated using Eqs. 6–6b is applied without any transformation for frequencies more than 10 Hz. For the lower frequencies, the correction gradually decreases up to a zero value for the minimum considered frequency (0.3 Hz) assuming logarithmic frequency dependence.

Obviously, the use of empirical relationships for estimating PGA from intensity may introduce additional uncertainty. Also, when considering only the recorded PGA values, it seems that the correction in the predictive model is not necessary for epicentral distances up to 200 km. We do not insist in using of the correction for peak amplitudes and leave the decision to the user discretion. However, we note that the correction leads to magnitude saturation of the acceleration amplitudes at relatively small epicentral distances (see Fig. 7c) that is a well-known phenomenon.

5 Discussion

The examples of distribution of the considered strong ground motion parameters versus epicentral distance, which were calculated using the developed equations (the AM variant, all corrections had been applied) for various magnitudes, are shown in Fig. 7a–c. The plots reflect the relationships between the considered ground motion parameters and the frequency content of the motion, which in turn depends on the characteristics of the source spectrum and the site amplification functions (Fig. 2c).

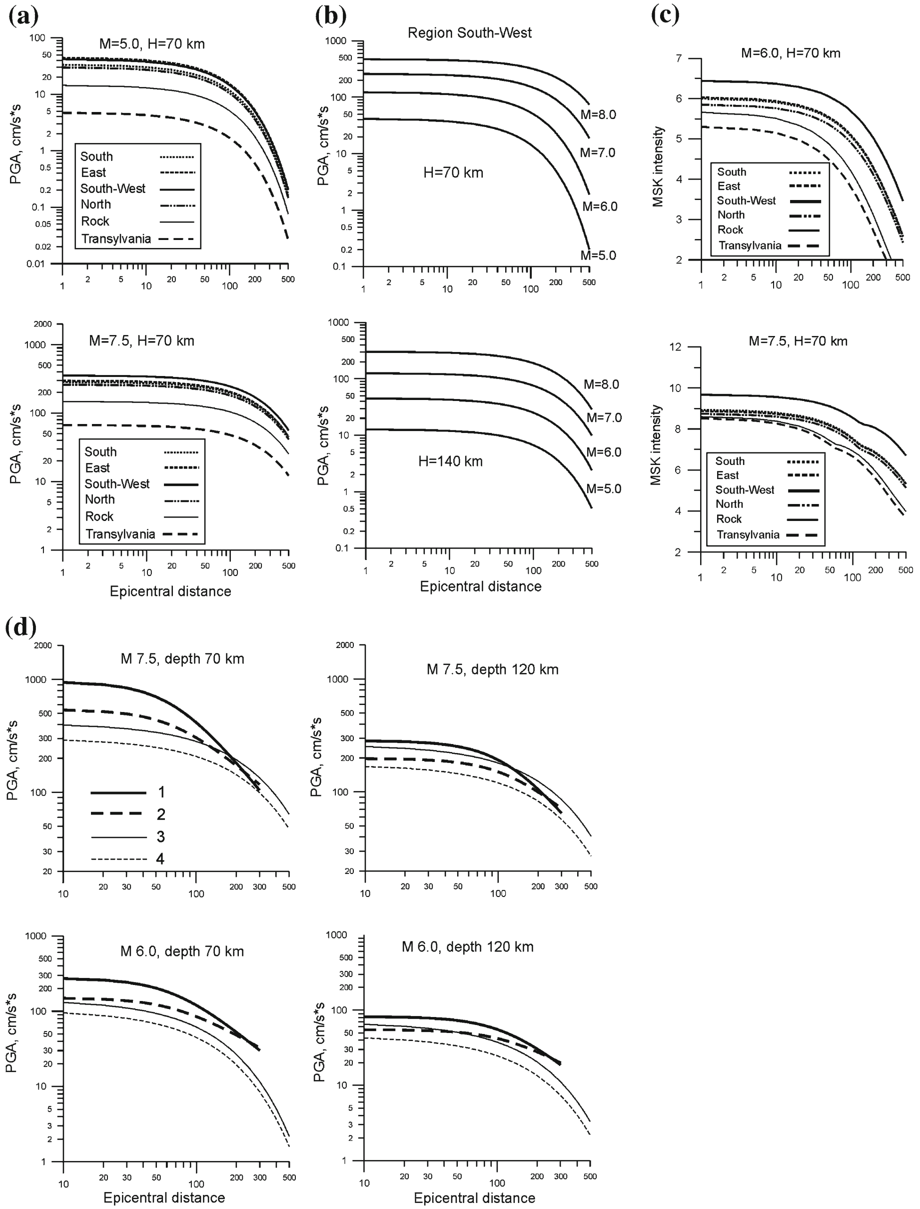

Fig. 7 Examples of the attenuation curves. (**a**–**c**) Comparison of the modelled PGA and MSK intensity curves for various zones, magnitudes (M), depth (H), and epicentral distances. (**d**) Comparison of the ground-motion models proposed recently for the Vrancea earthquakes by Lungu et al. (1995, 1997) (1—the Bucharest sector; 2—the Moldova sector) and developed in this work (3—the "South-West" region; 4—the "North" region)

Let us compare our relationships with the other regional models. Lungu et al. (1995, 1997) evaluated attenuation of maximum peak ground acceleration (PGAM) using records of three large Vrancea earthquakes, namely: March 4, 1977 ($M_W = 7.4$); August 30, 1986; May 30, 1990, in the following form

$$\ln PGAM = c_1 + c_2 M_{GR} + c_3 \ln D + c_4 h + \varepsilon \tag{7}$$

where M_{GR} is the Gutenberg-Richter magnitude; D is hypocentral distance; h is the focal depth; c_1, c_2, c_3, c_4, are the data dependent coefficients; ε is the parameter describing the data variation. Three attenuation models were evaluated using different data sets, which represent sectors (areas) located to three directions from the Vrancea zone. The data sets are the following: the whole data set; the Bucharest sector (azimuth 180°–270°, the "South-West" region in our study); the Cernavoda sector (azimuth 90°–180°, the "East" and "South" regions); the Moldova sector (azimuth $< 90°$, the "North" region).

The comparison of the PGA attenuation models constructed in this study and the relationships proposed by Lungu et al. (1995, 1997) is shown in Fig. 7d. The plots were calculated using moment magnitude M_W. The values of Gutenberg-Richter magnitude M_{GR} used in the Lungu et al. (1997) relationships were estimated from the M_W values using the relation $M_W = 1.09 M_{GR} - 0.36$, as given by Lungu et al. (1997). The peak ground acceleration values in Eq. 7 relate to hypocentral distance and focal depth. Therefore, for the direct comparison with our epicentral distance-dependent relationships, we performed the correspondent modification of the Lungu models. Also the PGAM relationships were evaluated for the maximum horizontal amplitudes from two components. The correspondent analysis of available records of large earthquakes showed that the ratio between the PGAM values and the amplitudes averaged between two horizontal components (geometric mean) is about 1.15. Therefore we show in the comparison our relationships based on mean-amplitude site amplification (the variant AM) and multiplied by the ratio.

The acceleration amplitudes obtained using our equations differ from the values resulted from the models developed by Lungu et al. (1997). However, the difference becomes smaller with the increase of earthquake depth. There is a general similarity between these models, namely: peak amplitudes of ground accelerations are larger for the "South-West" region (the Bucharest sector) than that for the North direction (the Moldova sector) at least for hypocentral distances less than 200–300 km.

Comparison of the observed and the modelled pseudo-spectral acceleration (PSA) values, based on the strong-motion data obtained at the strong-motion stations located in the city Bucharest, is shown in Fig. 8. The city is situated in the central part of the Moesian Platform (Fig. 1b). The cohesionless layered Quartenary deposits with a total thickness of more than 600 m are largely developed in the area (e.g., Mandrescu 1972; Moldoveanu et al. 2004). The lithological formations are characterized by strong lateral variations in depth and thickness.

For the comparison between the observed and the modelled data, we used one record (2 horizontal components) obtained by station INC during the earthquake of March 4, 1977 ($M = 7.4$, depth 95 km); eleven records (22 horizontal components) obtaineed during the earthquake of August 30, 1986 ($M_W = 7.2$, depth 130 km); and nine records (18 horizontal components) obtained during the earthquake of May 30, 1990 ($M_W = 6.9$, depth 90 km). The modelled PSA values were calculated using the AM and the AM1 variants of the prediction model (region "South-West"). In general, the modelled PSA values show a good agreement with the observed ones. The most data lay between the AM and the AM1 models and the AM1 variant may be considered as the reasonable estimation of the upper level of ground motion.

The records obtained at station INC exhibit relatively high PSA values at frequencies 0.5–1.0 Hz (Fig. 8c). The phenomenon of long predominant periods of ground motions in Bucharest from large earthquakes in the Vrancea area were extensively discussed (e.g. Ambraseys 1977; Lungu et al. 1995, 1999; Moldoveanu and Panza 2001). The influence of source mechanism (radiation pattern and directivity effect) was mentioned as one of the

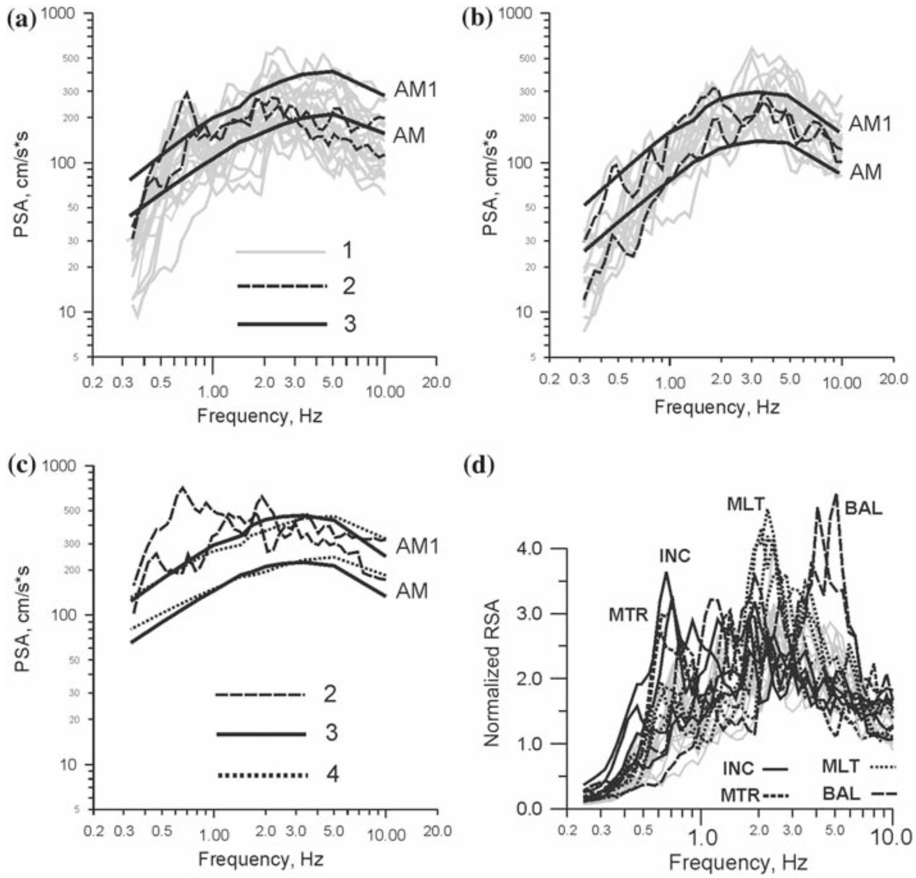

Fig. 8 Analysis of pseudo-spectral acceleration. (**a**–**c**) Comparison of 5% damped amplitudes (horizontal components) obtained during three large Vrancea earthquakes in Bucharest area and the modelled PSA values ("South-West" region, AM and AM1 variants). (**a**) the earthquake of August 30, 1986 (M_W 7.2, depth 130 km); (**b**) the earthquake of May 30, 1990 (M_W 6.9, depth 90 km); (**c**) the earthquakes of March 4, 1977 (M_W 7.4, depth 95 km) and November 10, 1940 (Mw 7.7, depth 140 km). 1—the observed data; 2—the data obtained at the station INC; 3—the modelled data; 4—the data modelled for the earthquake of November 10, 1940. (**d**) Normalized PSA (divided by PGA) calculated from the records obtained during the 1977, 1986 and 1990 earthquakes in the Bucharest area. The curves from particular stations are marked by the station index

explanations of the phenomenon (see also Sokolov et al. 2005). The design spectrum for the city (Lungu et al. 2006) has been constructed on the basis of the record. However, when comparing the observed and the modelled data, it is necessary to bear in mind the following. First, during the 1977 earthquake the phenomenon has been observed only at one component of a single record obtained in Bucharest. Second, not all stations, which were installed in the Bucharest area after 1977, did exhibit the same phenomenon during the earthquakes of 1986 and 1990 (Fig. 7d).

On other hand, the comparison shows that the frequency-dependent earthquake ground motion parameters may vary significantly within the city. In the present work we used the generalised prediction equations, which describe the average characteristics of ground motion through the large areas. The site-specific coefficients, which take into consideration geological features, should be introduced in addition to the generalised "regional-dependent" relationships. However, Mandrescu et al. (2007) concluded that at present state of knowledge it is impossible to determine certain zones within the city of Bucharest with different response to strong Vrancea earthquakes.

Note, that together with the modelled pseudo-spectral acceleration for the earthquake of March 4, 1977, we also show the modelled amplitudes for the earthquake of November 10, 1940 (Mw 7.7). The earthquake occurred at depth about 140 km. Even if the magnitude of the event was larger than that of the 1977 event, the severity of shaking in Bucharest during the earthquake was not stronger as compared with the 1977 earthquake (see also Bune et al. 1986).

Let us check the applicability of the developed strong-motion prediction equations for prediction of ground motion parameters along the territory of Romania. For this purpose we applied the following scheme. The territory was covered by a grid with $0.20° \times 0.20°$ spacing and the index of correspondent characteristic region was assigned to every node of the grid (see Fig. 2c). 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.

Estimation of the distribution of various engineering parameters of earthquake ground motion during the historical earthquakes is important both for the verification of reliability of seismic hazard and risk assessment and for the analyses of earthquake damage and seismic vulnerability. The modelled distribution of seismic intensity, peak ground acceleration and peak velocity along the Romanian territory during the earthquakes of March 4, 1977 (Mw 7.4, depth 95 km) and November 10, 1940 (Mw 7.7, depth 140 km), for which instrumental data are not available, are shown in Fig. 9a and 9b. 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.

Table 4 compares results of the modeling for the epicentral area (Focsani basin) and the Bucharest area with the available observed data and the results of site-dependent probabilistic seismic hazard assessment (Ismail-Zade et al. 2007; Sokolov et al. 2004a). Obviously, it is not possible to expect a perfect agreement between the available intensity observations and the results of the modelling; however the general features of the earthquake effect are reproduced quite adequately. The modelling shows that the expected PGA values could reach 0.3–0.4 g for some areas. We should note, however, that the PGA values may be overestimated for soft soil sites, because the site response in our calculations is considered to be linear during large earthquakes.

The prediction equations developed in this study are based on the generalised regional geological and site-conditions (Table 3). The effect of different soil profiles may be easily introduced using the correspondent amplification factors that modify the ground motion parameters obtained after application of the generalised model. However, no relationship between the site classes and the amplification effects has been established for the case of Romania so far and one has to use the amplification values developed for other regions, for example given by NEHRP's site amplification procedure (Wills et al. 2000; BSSC 1998). The correspondent amplification factors that, of course, should depend on the level of input

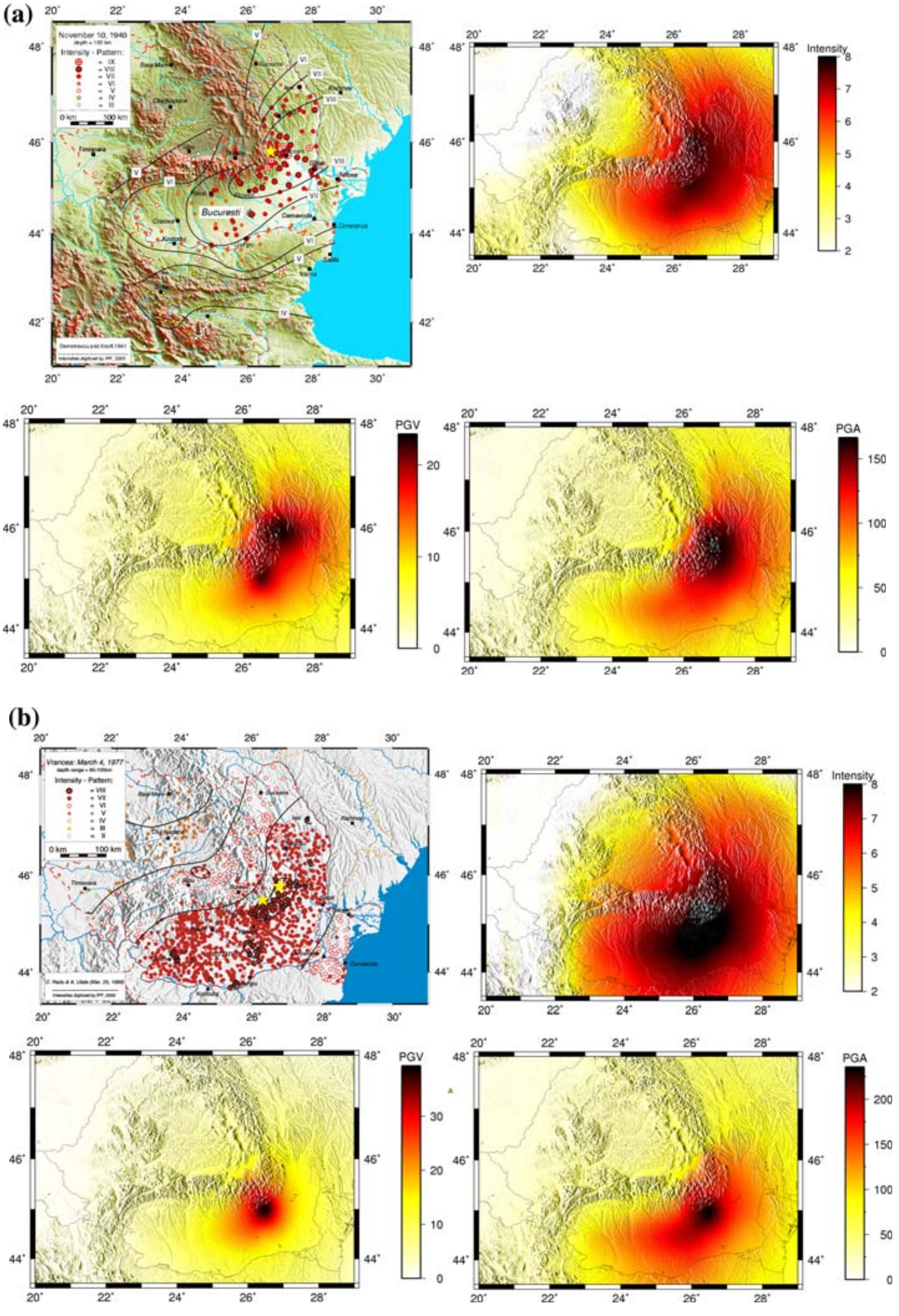

Fig. 9 The observed macroseismic maps and the modelled distribution of ground motion parameters (MSK intensity, peak ground acceleration and peak ground velocity) for the major Vrancea earthquakes. (**a**) the earthquake of November 10, 1940 (Mw 7.7, depth 140 km); (**b**) the earthquakes of March 4, 1977 (M_W 7.4, depth 95 km)

Table 4 Values of ground motion parameters, which were observed (in parentheses) and modelled for large Vrancea earthquakes

	Intensity (MSK)		PGA (cm/s^2)		PGV (cm/s)	
	Focsani basin	Bucharest	Focsani basin	Bucharest	Focsani basin	Bucharest
Earthquake of 1977	8.4 (VIII)	8.0 (VII–VIII)	200–400	150–300 (160, 190)[a]	25–45	10–25
Earthquake of 1940	8.6 (VIII–IX)	7.4 (VII–VIII)	130–350	100–180	10–25	10–15
PSHA 475 years	>IX	VIII	300–600	240–450	–	–
PSHA 100 years	VIII	VII–VIII	150–300	110–270	–	–

The lower and upper limits of the modelled parameters were estimated using the AM and AM1 variant of attenuation relationships. The results of site-dependent probabilistic seismic hazard assessment (Ismail-Zade et al. 2007; Sokolov et al. 2004a) are shown for comparison. [a]the earthquake of 1977 was recorded in Bucharest by one station (INC). Here we show the maximum amplitudes from the horizontal components motion are normalized to the reference soil classes assigned to our characteristic regions (Table 3).

6 Conclusion

Results of our recent strong-motion studies in Romania (e.g. Sokolov and Bonjer 2006; Sokolov and Wenzel 2007; Sokolov et al. 2004b; Sokolov et al. 2005) allow constructing the “azimuth-” or “region-dependent” prediction equations for the territory in terms of various engineering earthquake ground motion parameters and seismic intensity. The Fourier amplitude spectrum (FAS) source scaling and attenuation models and the generalised site amplification functions were used, as the basis, for evaluation of the ground motion models. The equations, in contrast to the existing empirical ones (e.g. Marza and Pantea 1994; Lungu et al. 1995, 1997), do not require the special procedures of conversion between the various ground motion parameters.

When evaluating the Fourier amplitude spectrum for given earthquake magnitude and depth, we intentionally used the generalised parameters of the earthquake source (seismic moment and stress parameter) and the simple models of source scaling and attenuation. In many cases, the detailed features of the slip distribution are unknown for both recorded earthquakes and future events. Thus, we analyze conditions, at which the simple models can describe the real events. The situation is common in the practice of seismic hazard assessment, as well as in the case of Shakemap generation.

The developed prediction equations, despite of their simplicity, reveal a good agreement with the observed data and clearly reflect the azimuth (or region) dependent distribution of ground motion parameters during the Vrancea earthquakes. We suggest to use the presented equations for the rapid estimation of seismic effect after strong earthquakes (Shakemap generation) and seismic hazard assessment, both deterministic and probabilistic approaches. The coefficients of the equations, as well as a simple FORTRAN code for practical calculations, are available from the correspondent author (V. Sokolov).

However, we should mention several weak points in our results, which are the main topics of the future research. First, bearing in mind the large variability of ground motion parameters, it seems to be important to introduce the site-specific coefficients that take into consideration geological, geomorphological, and geotechnical characteristics of the sediments and their thickness. Second, a special consideration should be given to the problems related to assessment of the magnitude- and depth-dependent correction for the case of peak ground velocity and pseudo-spectral acceleration at different frequencies. Third, for the case of large magnitude earthquakes, it is necessary to take into account the source dimension and to apply a hybrid technique, which considers the low- and high-frequency ranges separately. A special study should be performed for validation whether the developed equations could be used for neighbouring, with Romania, countries, e.g. Moldova, Bulgaria, and Ukraine.

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