Harmonization of seismic hazard and risk reduction in the Vrancea zone: scientific results of a NATO research project

Zaicenco, Anton and Craifaleanu, Iolanda-Gabriela and Lungu, Dan and Paskaleva, Ivanka and Özcebe, Güney

Institute for Geophysics and Geology, Moldovan Academy of Sciences, Chisinau, Moldova, National Institute for Building Research, INCERC, Bucharest, Romania, Technical University of Civil Engineering, UTCB, Central Laboratory for Seismic Mechanics and Earthquake Engineering, Sofia, Bulgaria, Department of Civil Engineering, Middle East Technical University, Ankara, Turkey

2009

HARMONIZATION OF SEISMIC HAZARD AND RISK REDUCTION IN THE VRANCEA ZONE: SCIENTIFIC RESULTS OF A NATO RESEARCH PROJECT

Anton ZAICENCO[1], Iolanda-Gabriela CRAIFALEANU[2,3], Dan LUNGU[3], Ivanka PASKALEVA[4], Güney ÖZCEBE[5]

ABSTRACT

The paper presents some of the main scientific results achieved in the framework of a recently completed NATO Science for Peace and Security research project. The project aimed to harmonize the different seismic hazard maps of Romania, Moldova and Bulgaria and to develop standard maps in Eurocode 8 format, reflecting the real trans-boundary geophysical effects of the seismic phenomenon. In order to achieve these results, an important amount of research work in the field was carried out by the project teams of the three countries. The project also involved training of young scientists in the fields of seismic hazard, vulnerability and risk, organizing of seminars and workshops with international experts and upgrading the national seismic networks with new digital equipments. The general coordination of project activities and the evaluation of the project progress were performed by a scientific team from the Middle East Technical University (METU) in Ankara, Turkey.

Keywords: seismic hazard, seismic risk, Vrancea zone, NATO research project

REZUMAT

Articolul prezintă câteva dintre principalele rezultate ştiinţifice obţinute în cadrul unui recent proiect de cercetare NATO desfăşurat în cadrul programului „Ştiinţa pentru pace şi securitate”. Proiectul a urmărit armonizarea diferitelor hărţi de hazard seismic din România, Moldova şi Bulgaria şi dezvoltarea de hărţi standardizate în format Eurocode 8, care să reflecte efectele geofizice reale, transfrontaliere ale fenomenului seismic. Pentru a obţine aceste rezultate, un volum important de cercetări în domeniu a fost realizat de echipele de proiect din cele 3 ţări. Proiectul a implicat, de asemenea, pregătirea tinerilor specialişti în domeniile hazardului, vulnerabilităţii şi riscului seismic, organizarea de seminare şi workshop-uri cu experţi internaţionali, precum şi modernizarea reţelelor seismice naţionale cu noi echipamente digitale. Coordonarea generală a activităţilor şi evaluarea progresului proiectului au fost realizate de către o echipă ştiinţifică de la Universitatea Tehnică a Orientului Mijlociu (METU) din Ankara, Turcia.

Cuvinte cheie: hazard seismic, risc seismic, zona Vrancea, proiect de cercetare NATO

1. INTRODUCTION

The project was carried out between 2005 and 2009, by scientists from the Republic of Moldova, Romania and Bulgaria. The organizations participating in the project were: the Institute of Geophysics and Geology, IGG, Chisinau, the National Institute for Building Research, INCERC, Bucharest, and the Central Laboratory for Seismic Mechanics and Earthquake Engineering, CLSMEE, Sofia. The evaluation of the project progress and general coordination of the project activities were performed by a team from the Middle East Technical University, METU, in Ankara, Turkey. The project aimed the development of a unique approach to the seismic hazard assessment from the Vrancea source for all affected countries.

[1] Institute for Geophysics and Geology, Moldovan Academy of Sciences, Chisinau, Moldova, anton.az@gmail.com
[2] National Institute for Building Research, INCERC, Bucharest, Romania, iolanda@incerc2004.ro
[3] Technical University of Civil Engineering, UTCB, Bucharest, Romania, lungud@utcb.ro
[4] Central Laboratory for Seismic Mechanics and Earthquake Engineering, Sofia, Bulgaria, paskalev_2002@yahoo.com
[5] Department of Civil Engineering, Middle East Technical University, Ankara, Turkey, ozcebe@metu.edu.tr

2. SCOPE AND OBJECTIVES OF THE PROJECT

The main core of the project was seismic hazard assessment of Vrancea zone, taking into account directivity effects, local soil conditions and vulnerability of the existing building stock. In order to enhance the scientific infrastructure of the participating countries, it has also been proposed to upgrade the national seismic networks with new digital accelerometers and other equipments. In this way, acquisition of high-quality earthquake records in the future will contribute to better understanding of geodynamic processes at regional level.

3. SCIENTIFIC RESULTS

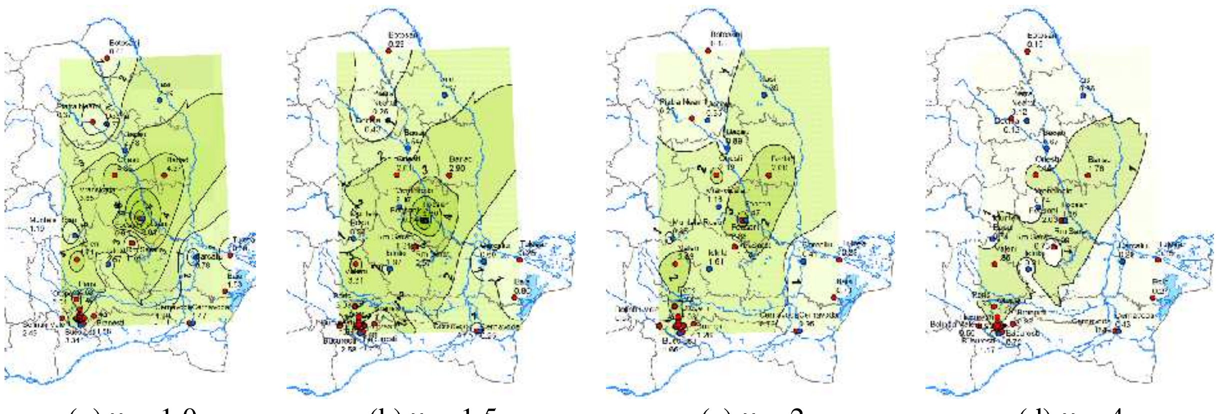
3.1. ROMANIA

3.1.1. Shake Maps of Strength and Displacement Demands for Romanian Vrancea Earthquakes

An extensive study was performed at INCERC on Vrancea earthquakes having moment magnitude $M_w \geq 6.0$, recorded in Romania during the last 30 years. In the first phase of the study, maps were generated for peak ground acceleration (PGA), peak ground velocity (PGV), effective peak ground acceleration (EPA), effective peak ground velocity (EPV) and control (corner) periods of response spectra (T_C and T_D). The second phase of the study focused on the development of maps for linear elastic acceleration and displacement spectra while, in the third phase of the study, maps were generated for inelastic, constant ductility, acceleration and displacement spectra ordinates.

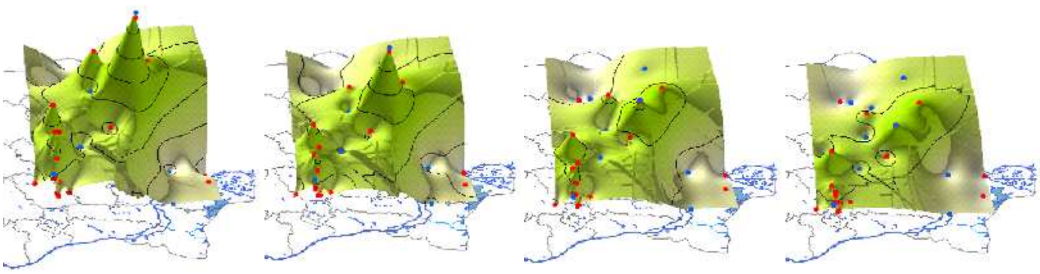
The following Vrancea events were considered: August 30, 1986 (moment magnitude $M_w = 7.1$, focal depth $h = 133$ km), May 30, 1990 ($M_w = 6.9$, $h = 91$ km), May 31, 1990 ($M_w = 6.4$, $h = 79$ km) and October 27, 2004 ($M_w = 6.0$, $h = 96$ km). For each event, seismic data was mapped for the whole territory of Romania and for the area of the capital city, Bucharest. Records obtained from the seismic networks of Moldova and Bulgaria were also included, where available.

Based on map ordinates, interpolation surfaces and contours of constant values were computed and plotted, by using GIS software (Craifaleanu et al., 2006, Lungu and Craifaleanu, 2008). Some examples are given in Figures 1-3.



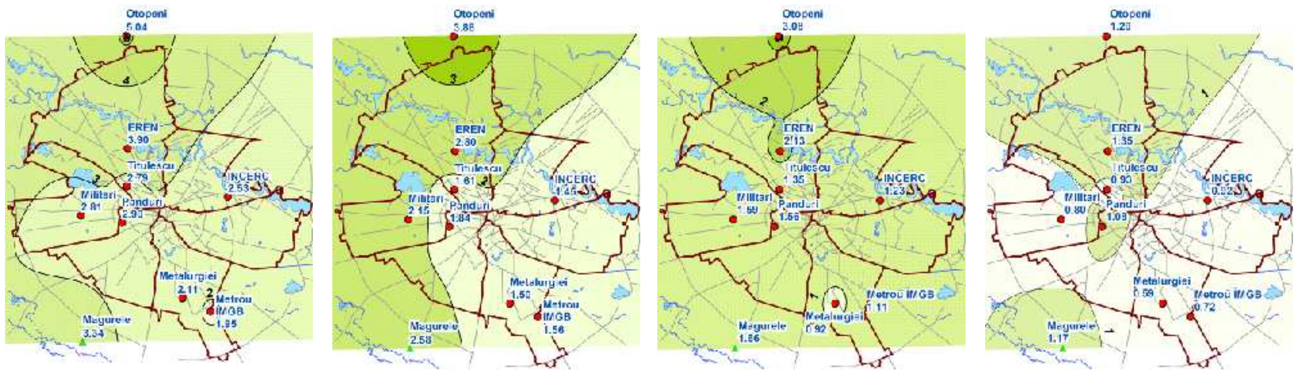
(a) $\mu = 1.0$ (b) $\mu = 1.5$ (c) $\mu = 2$ (d) $\mu = 4$

Figure 1. August 30, 1986 earthquake. Distribution of elastic ($\mu = 1.0$) and inelastic ($\mu = 1.5, 2.0, 4.0$) spectral acceleration for structure period T = 0.5 s



(a) $\mu = 1.0$ (b) $\mu = 1.5$ (c) $\mu = 2$ (d) $\mu = 4$

Figure 2. Three-dimensional view of the interpolation surfaces in Fig. 1



(a) $\mu = 1.0$ (b) $\mu = 1.5$ (c) $\mu = 2$ (d) $\mu = 4$

Figure 3. Bucharest, August 30, 1986 earthquake. Distribution of elastic ($\mu = 1.0$) and inelastic ($\mu = 1.5, 2.0, 4.0$) spectral acceleration for structure period $T = 0.5$ s

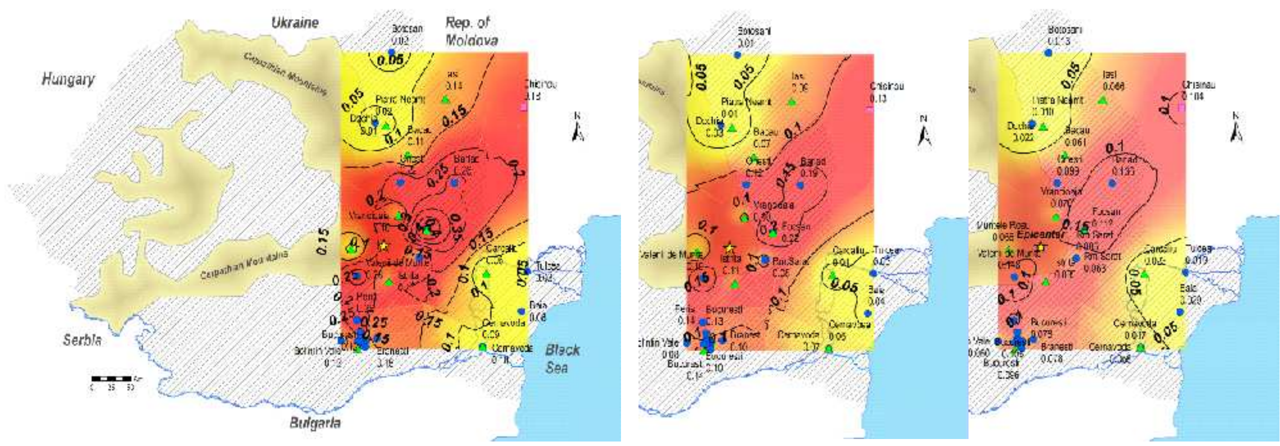
By examining the maps, a clear tendency of decreasing spectral ordinates with increasing ductility can be observed. The spatial distribution of spectral accelerations becomes more uniform as ductility increases. This phenomenon was observed on all maps, irrespective of the structure period for which the spectral ordinates were computed. However, the interpolation surface does not flatten uniformly, as the rate of variation of spectral ordinates with ductility is different from one ground motion record to another (Figure 2).

Vibration period of SDOF system also has an important influence on spectral accelerations. However, in the long-period range, i.e. for $T = 1.5$ s, the amplitude of this variation attenuates considerably, as a consequence of the frequency contents of the ground motions.

Contour maps are also sensitive to factors like: number of stations that provided seismic records and values of the numerical parameters used to generate the interpolation surface. One of the most significant conclusions is that the spatial distribution of seismic strength demands is more uniform for structures with inelastic behaviour than for the structures behaving elastically. As a result, for common structures in which inelastic behaviour is allowed under the design earthquake, the influence of the other factors affecting spatial distribution is less important than anticipated.

3.1.2. Assessment of the Damage Potential and of the Building Performance Demands for Romanian Vrancea Earthquakes

Maps were generated for two values of structure period, $T = 0.5$ s and $T = 1.0$ s, and for



a) $DM.\mu_u = 2$ b) $DM.\mu_u = 4$ c) $DM.\mu_u = 6$

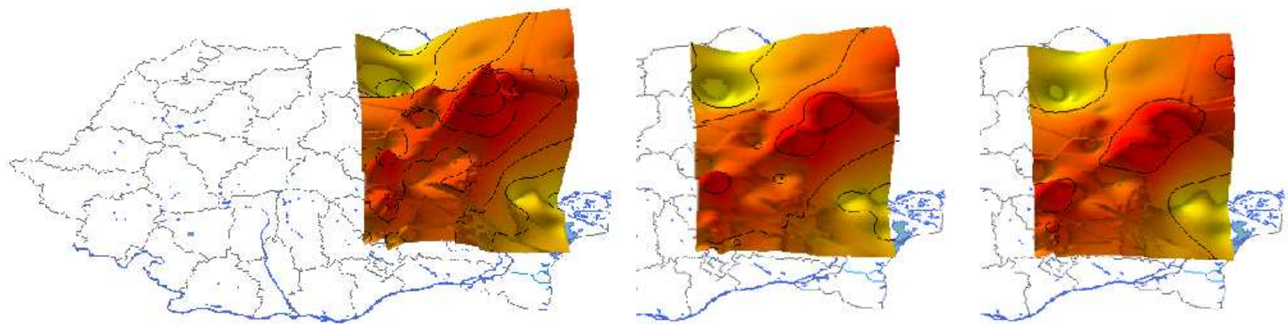
Figure 4. Spatial distribution of yield strength demands (C_y) for the Vrancea earthquake of August 30, 1986. Structure period $T = 0.5$ s

three values of the product $DM.\mu_u$, i. e. 2, 4 and 6, where DM is the Park-Ang damage index and μ_u is the ductility under monotonic loading. By mapping the yield coefficient ordinates, C_y, for the 35 seismic stations considered, the maps in Figures 4 and 6 were obtained. The maps display the spatial distribution of the yield strengths values required to keep the structural damage below a certain level, given the value of the structure ductility under monotonic loading (Craifaleanu, 2008a). Figure 5 shows 3D representations of the interpolation surfaces.

The detailed spatial distribution of yield strength demands for the city of Bucharest and structure period T = 0.5 s is shown in Figure 6, for the same values of $DM.\mu_u$ mentioned above.

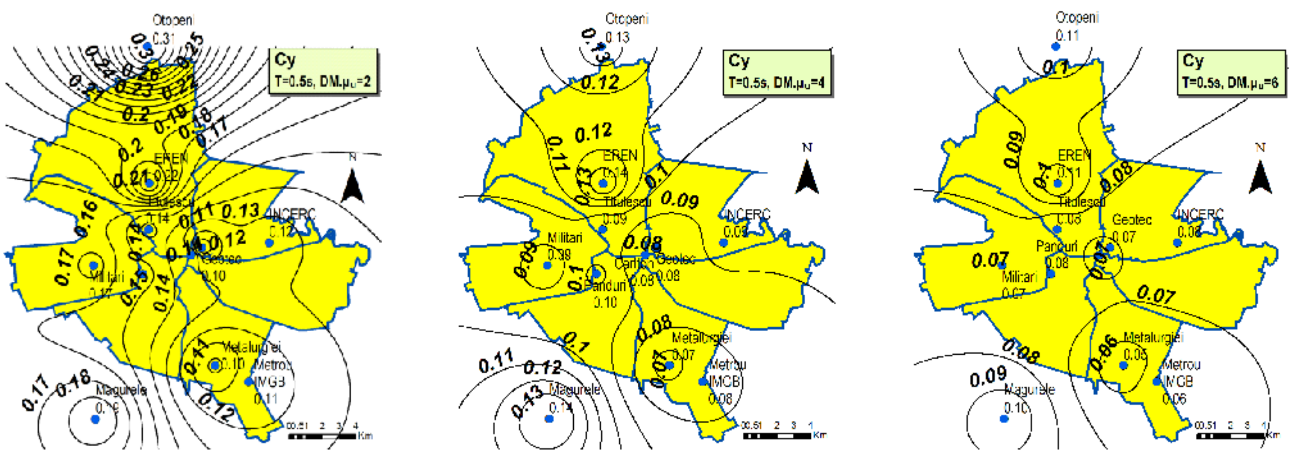
3.1.3. Comparison of the Requirements of Present and Past Romanian Seismic Design Codes, Based on the Required Structural Overstrength

As a part of the process of harmonization with European standards, a substantial effort has been made in Romania in recent years to implement regulations concerning the seismic design of buildings. Most of the provisions of Eurocode 8 Part 1 (CEN, 2004) were adopted (with a number of required adjustments) in the new Romanian seismic design code, P100-1/2006 (MTCT, 2006). This new code introduces important changes in comparison with the previous one, P100-92 (MLPAT, 1992), one of the most significant being the evaluation of seismic forces.



a) $DM.\mu_u = 2$ b) $DM.\mu_u = 4$ c) $DM.\mu_u = 6$

Figure 5. Three-dimensional view of the interpolation surfaces in Figure 4

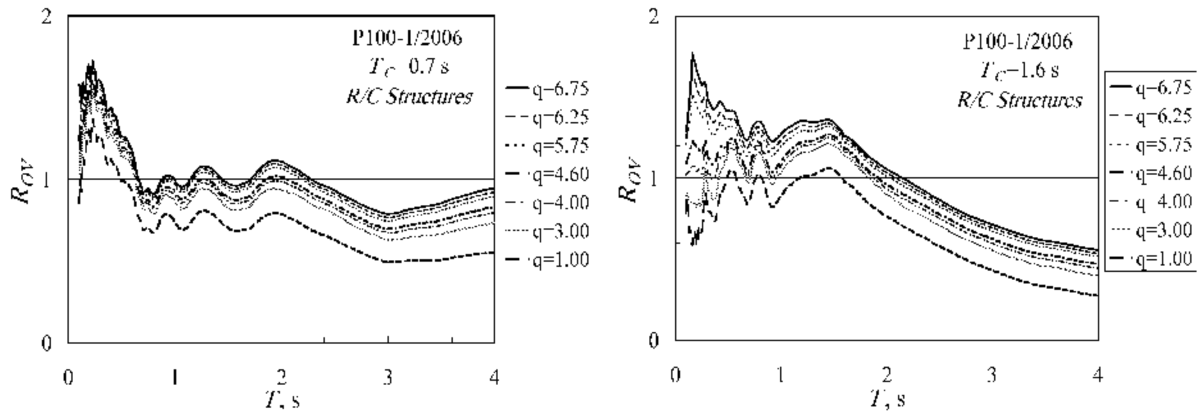


a) $DM.\mu_u = 2$ b) $DM.\mu_u = 4$ c) $DM.\mu_u = 6$

Figure 6. Spatial distribution of yield strength demands (C_y) in Bucharest, for the Vrancea earthquake of August 30, 1986. Structure period T = 0.5 s

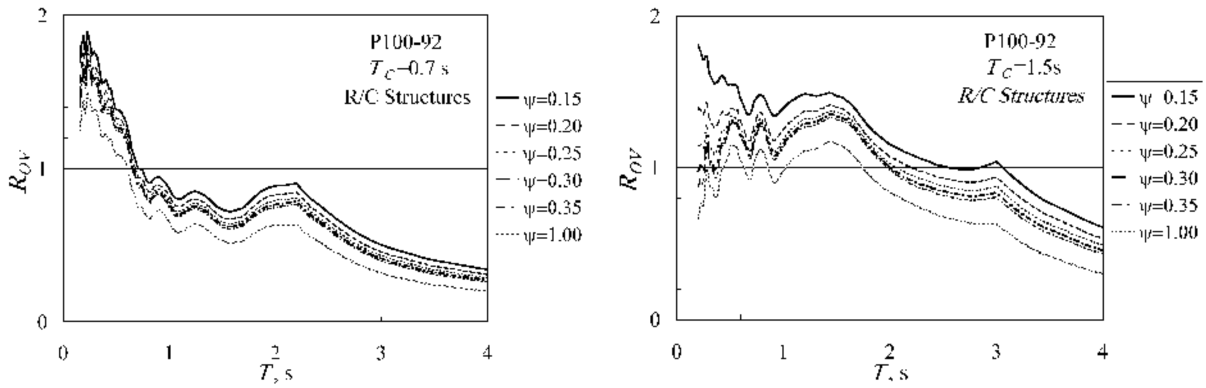
A comparative analysis of behavior factors and seismic forces specified by two versions of the code is performed in this paper with reference to the provisions of Eurocode 8. As a result, required overstrength is evaluated for both versions of the Romanian seismic design code. Based on the results, severity assessments are made (Craifaleanu, 2008b).

The required overstrength is expressed by means of factor R_{OV}, calculated as a ratio between the demand, expressed by actual spectral ordinates with 10 % probability of exceedance (determined by considering a lognormal distribution for a set of real records), and the code specified design spectra. Both types of spectra were determined for the same specified value of the inelastic behaviour factor (i.e. the q factor in the new code and the ψ coefficient in the old code, respectively).



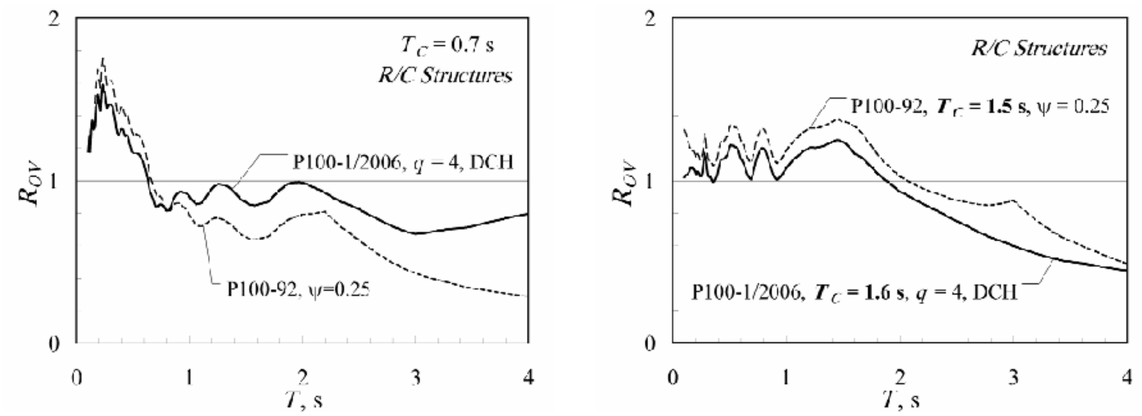
a) b)

Figure 7. P100-1/2006. R_{ov} values for reinforced concrete structures of high ductility class (DCH)



a) b)

Figure 8. P100-92. R_{ov} values for reinforced concrete structures



a) b)

Figure 9. Comparative diagrams of R_{ov}

The study demonstrated that the required overstrength for the structures designed to resist the seismic forces specified by the new code was lower than that in the old code. This provides an indication of a more conservative character of the new code.

3.2. BULGARIA

The wave field radiated by the intermediate-depth (70 to 170 km) Vrancea earthquakes, mainly at long periods (T > 1s), attenuates less with distance, compared to the wave field generated by the earthquakes located in other seismically active zones in Bulgaria. The regional seismic hazard in NE Bulgaria, where the town of Russe is a major industrial and cultural centre, is controlled mainly by the Vrancea intermediate-depth events. Urban areas located at fairly large distances from earthquake sources may thus be prone to severe earthquake hazard as well as the near field sites. The available strong ground-motion database is too limited to reliably quantify the magnitude scaling and the attenuation characteristics of large magnitude earthquakes.

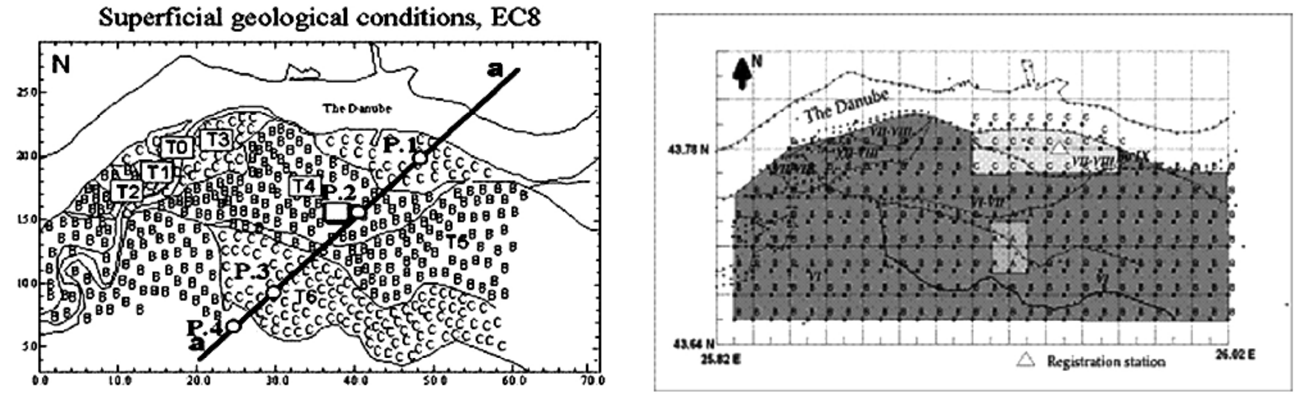
The major results formulated by the Bulgarian team are:

– The mapping of the local geological condition at the town of Russe following different soil classification – Bulgarian regulations, Eurocode 8 and UBC;

– The study of damaging effects of the recent strong Vrancea quakes occurred in the 20th century laid foundation for seismic input modeling and estimates of the seismic loading. Computations on the contribution of the seismic source and of the local site conditions to the seismic input were performed, applying a neo-deterministic seismic hazard assessment procedure (Panza et al., 2001; Kouteva et al., 2008a, c; Paskaleva et al., 2008);

– The seismic monitoring in the region of Russe as a contribution to the sustainable development of the region. Data produced by seismic-monitoring instruments are transformed into information for the decision makers (e.g. emergency managers, earthquake engineers) and include analytical aspects that depend on the type of data and the nature of decision (Kouteva and Paskaleva, 2008b).

A brief analysis of available records of the strong intermediate-depth Vrancea earthquakes with M_w > 6.5 (Nenov et al, 1990; Ambraseys et al., 2002) has demonstrated the significant effect of the earthquake source mechanism on the seismic motion, which clearly differ in local geological conditions and epicentral distances. Synthetic seismic signals were computed using the neo-deterministic procedure for seismic wave propagation modeling (Panza et al., 2001; Kouteva et al., 2008 a, c). For the validation of the computed signals at Russe, three local models, corresponding to Eurocode 8 ground type C ($V_{s,30}$ = 325 m/s) have been used: (a) deep model, top layer (of type C) 150 m thick, (b) intermediate model, top layer 60 m thick and



a) b)

Figure 10. a) Mapping of local site conditions in Russe using the Eurocode 8 ground type classification, b) Geological zonation of the city of Russe, according to UBC, overlapped with the observed macroseismic intensity, I, MSK-64, due to the March 4, 1977, Vrancea earthquake (Simeonova et al, 2006)

(c) shallow model, top layer 30 m thick. For more details see Kouteva et al. (2008 a). By varying the parameters describing geometry and kinematics of the seismic source, several parametric analyses were performed (Figure 11). These results have demonstrated that the shallow local models give dynamic coefficients closer to the EC8 recommendations for the considered frequency interval, 0-5 Hz.

The proposed two Vrancea scenario earthquakes are listed in Table 1. The seismic input computed according to Table 1 is shown in Figures 12 and 13.

Table 1.

Scenario Earthquakes - strong intermediate-depth Vrancea quakes

Scenario*	Lat.	Long.	M_w	Focal depth	Strike angle	Dip angle	Rake angle
Sce_1	45.76° N	26.53° E	7.2	132.7 km	240°	72°	97°
Sce_2	45.80° N	26.70° E	7.8	150.0 km	225°	60°	80°

* Sce_1 seismic source corresponds to the 1986 Vrancea earthquake (August 30), (Dziewonsky et al. 1991) and Sce_2 corresponds to the Vrancea 1940, Nov. 10, earthquake (Radulian et al., 2000 and references therein; Lungu et al.2004)

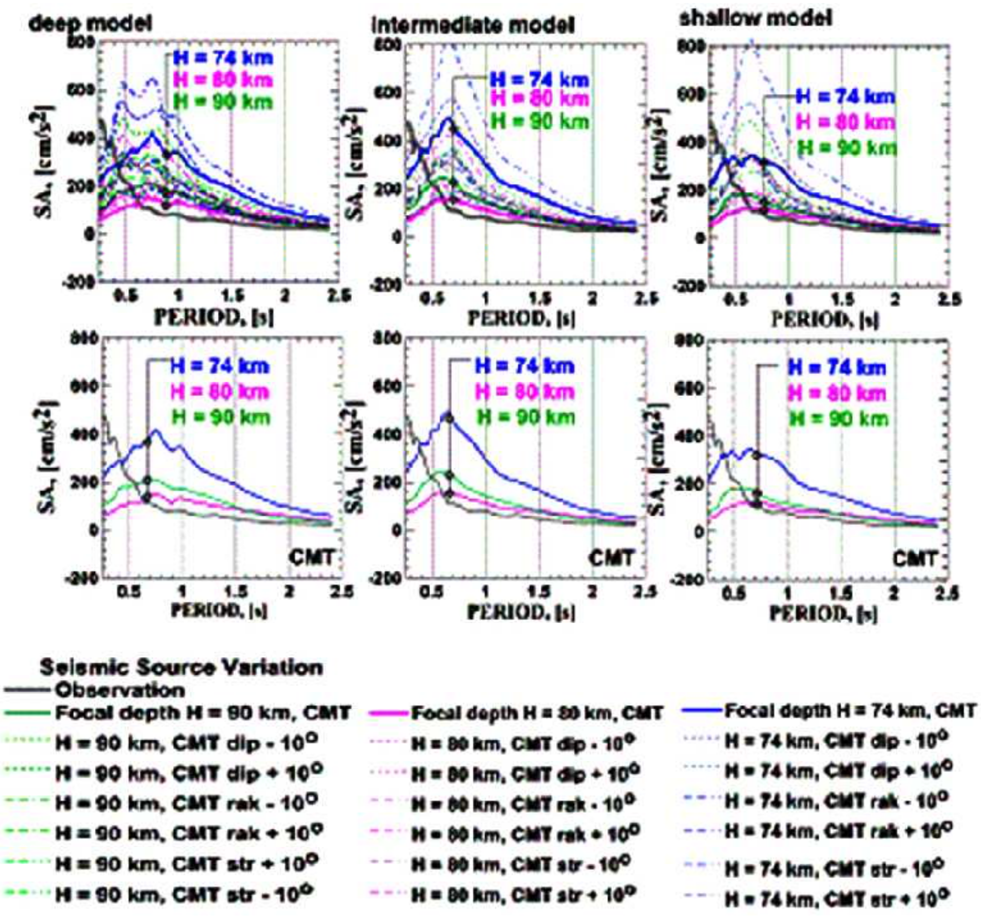


Figure 11. Elastic acceleration response spectra, computed for 5 % damping. Synthetics against observation (solid grey line), Vrancea earthquake, May 30, 1990, M_w = 6.9

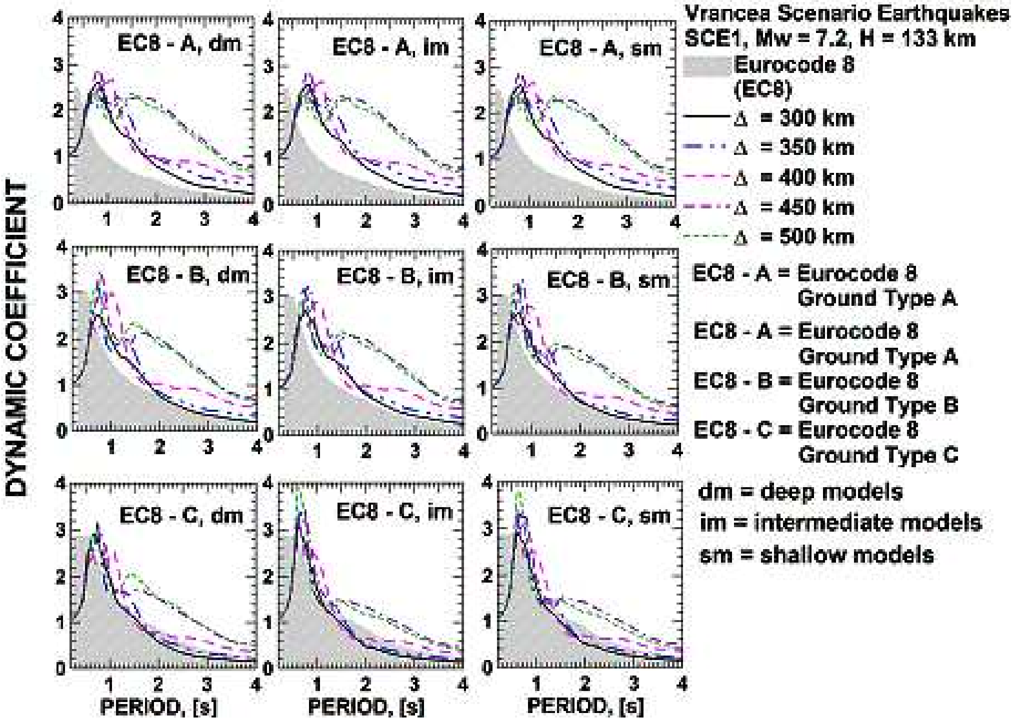


Figure 12. Vrancea scenario earthquake, strong event, SCE1 – Table 1

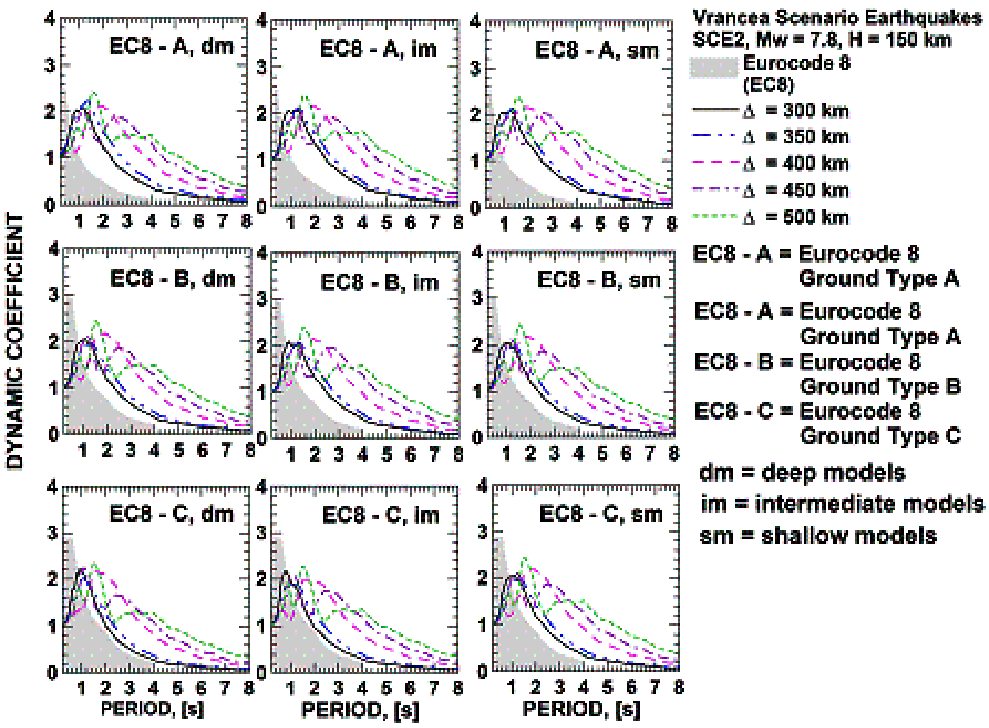


Figure 13. Vrancea scenario earthquake, extreme event, SCE 2 –Table 1

The major outcome of the analysis of the results, shown in Figures 12 and 13, can be summarized as follows:

– Computed synthetic seismic input for shallow earthquakes is consistent with the Eurocode 8 requirements;

– For the intermediate-depth earthquakes, local models with a thin top layer of type C supply synthetic seismic signals, that are quite close to the observed ones;

– The site response due to both, shallow and intermediate-depth, earthquakes is significantly influenced by the earthquake source mechanism;

– Dynamic coefficients computed for accelerograms (observed and simulated) due to strong intermediate-depth Vrancea earthquakes exceed significantly the values recommended by the Eurocode 8 (EC8) for periods $T > 1$s.

3.3. REPUBLIC OF MOLDOVA

3.3.1. Recurrence and Probability of Vrancea Intermediate-Depth Earthquakes

Three methods were employed to make estimates of recurrence intervals: (a) classical Gutenberg-Richter (Gutenberg and Richter, 1956), (b) maximum entropy principle (MEP) modified for estimating the recurrence of strong earthquakes (Berrill and Davis, 1980, Dong *et al.,* 1984) and (c) Huo and Hwang's (Hwang and Huo, 1994) modification of the recurrence law containing characteristics of a stochastic distribution. An analysis of recurrence relationships was performed for two types of magnitudes, for different time intervals and by assigning alternative values of maximum possible earthquake magnitude. The probability of an earthquake occurring in a specified magnitude range and in a specified time limit was estimated. The dependence of final estimates on the choice of values of M_{min} and M_{max} and on sample size was demonstrated. From the analysis of established intervals of recurrence it follows that the recurrence period of earthquakes with $M = 7.0$ is from 30 to 60 years with a relatively high probability of $R = 0.5$-0.7 (for $T = 50$ years). For magnitude $M_{G-R} = 7.5$ ($M_w = 7.7$) the recurrence interval varies from 100 (most pessimistic estimation) to 380 years (most optimistic estimation) with a probability of $R = 0.1$-0.25 (for $T = 50$ of years).

The catalogues of earthquakes compiled by C. Radu (Radu, 1982, 2003) provide values of G-R magnitude. In parallel, the same calculations are done for the catalogue ROMPLUS (1998) using magnitude M_w, obtained from correlation formulas or direct definitions of the seismic moment. Magnitudes M_w are recommended for estimating seismic hazards within the framework of the Global Seismic Hazard Assessment Programme (GSHAP, 1993) as the characteristic that most adequately reflects the size of an earthquake and is not affected by saturation and has plain physical sense. Actually, the G-R magnitudes are identical to magnitudes M_s (determined from surface waves). In general, magnitudes M_s do not pertain to intermediate depth earthquakes (with $h > 60$-70 km); however, such magnitudes were frequently used in previous years to calculate seismic hazards from Vrancea intermediate earthquakes. Therefore, estimates of recurrence parameters are made for both types of magnitudes.

The dependence of final estimates on the choice of values of M_{min} and M_{max} and on sample size is shown. From the analysis of established intervals of recurrence it

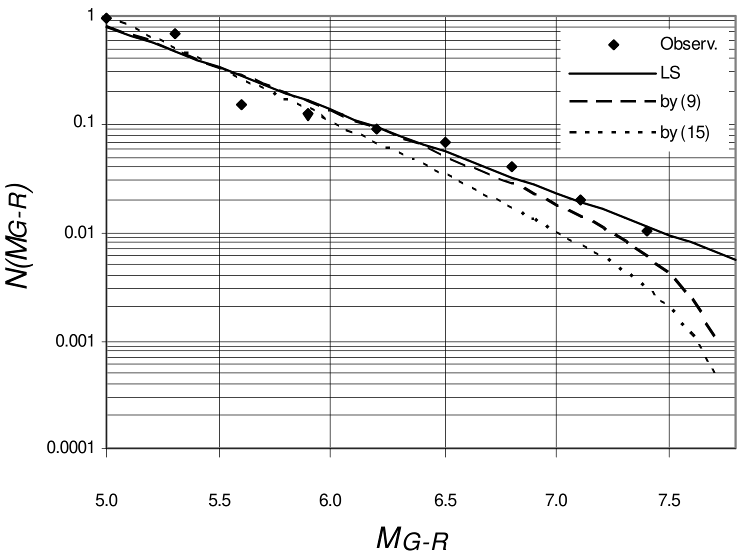


Figure 14. Recurrence Graphs for Vrancea Earthquakes with $M \geq 5.0$

Table 2.

Recurrence Intervals and the Probability of Strong Vrancea Earthquakes (data set 1)

Data of strong real events	$M_{G\text{-}R}$	Recurrence interval			Probability $R_{T=50}$(m)	
		Gutenberg-Richter	Hwang method	From max. entropy	by (8)	by (16)
	6.5	18	20	29	0.938	0.813
	6.6	21	24	38		
1990.05.30	6.7	26	30	48	0.858	0.648
	6.8	31	37	61		
	6.9	36	45	78		
1986.08.30	7.0	44	57	101	0.683	0.389
	7.1	52	73	133		
1977.03.04	7.2	62	94	177	0.553	0.245
	7.3	74	125	243		
1940.11.10	7.4	88	172	345	0.432	0.135
	7.5	106	254	520	0.377	0.092

follows that the recurrence period of earthquakes with M = 7.0 is from 30 to 60 years with a relatively high probability of R=0.5-0.7 (for T = 50 years). For magnitude $M_{G\text{-}R}$= 7.5 (M_w= 7.7) the recurrence interval varies from 100 (most pessimistic estimation) to 380 years (most optimistic estimation) with a probability of R = 0.1-0.25 (for T = 50 of years).

3.3.2. Seismic Microzonation of Chisinau: a Tool for Reducing Seismic Risk

Dynamic properties of soft soils in Chisinau City exposed to seismic hazards from Vrancea seismic sources are investigated. Empirical transfer functions for soft soils were determined using earthquake and ambient noise records. Available geotechnical surveys (shear wave velocities v_s) allowed employing 1-D and 2-D numerical methods for considering soft soil effects on the parameters of ground shaking. Observations of structural damage during the 1977 and 1986 seismic events allowed the development of relationships between the parameters of ground shaking and MSK intensities. A study of the amplification capacity of sites provided the basis for locating zones with varying seismic intensities and for developing a new seismic microzonation map of Chişinău. The iso-intensity map using the MSK scale shows that variations in the expected intensity values ranged between VII and VIII for the city's area. A methodology of seismic microzonation based on a complex study of soil dynamic properties was developed.

The following data and methods were employed in this study.

– Geological and geotechnical data for 1210 sites;

– Records of Carpathian earthquakes (Gutenberg-Richter magnitude 2.8 ≤ M_{GR} ≤ 7.2 and focal depth 100 < H ≤ 150 km) at 14 sites. Strong earthquakes (M_{GR} > 6.0) were recorded by accelerometers operating in the triggering mode, and weak events were recorded by six permanently operational portable seismic stations;

– Microtremor measurements at 85 sites. Data were recorded for 180 seconds (s) three times at each site. The measurements were made during the night using C5C seismometers when the contaminating effects of traffic and industrial noise were minimal;

– Measurements of shear wave velocity at 118 points using the down-hole method;

– 1-D (Ratnikova, 1984) and 2-D (Zahradnik, 1982) numerical modeling of the amplification capacity of soils.

Macroseismic (damage) data during three strong Vrancea earthquakes: 1845 inspected buildings after the 1977 event, 2496 after the 1986 quake and 660 after the 1990 event.

Chisinau is the capital of the Republic of Moldova and has a population of more than 700,000. It is situated at ≈200 kilometers from the Vrancea epicentral zone. During the last century, the city has experienced several strong earthquakes (Table 3). One of the first attempts to produce a seismic microzonation map of Chişinău dates back to 1941 (Figure 15).

Table 3.

Recorded PGA and Observed Intensities from Strong Vrancea Earthquakes in Chisinau

Earthquakes	Magnitude M_{GR}	Hypocentral distance, km	Max PGA, cm/s^2	Max MSK intensity
November 10, 1940	7.4	210	–	8
March 4, 1977	7.2	200	99.16	7
August 30, 1986	7.0	230	232.5	8
May 30, 1990	6.9	210	204.3	6

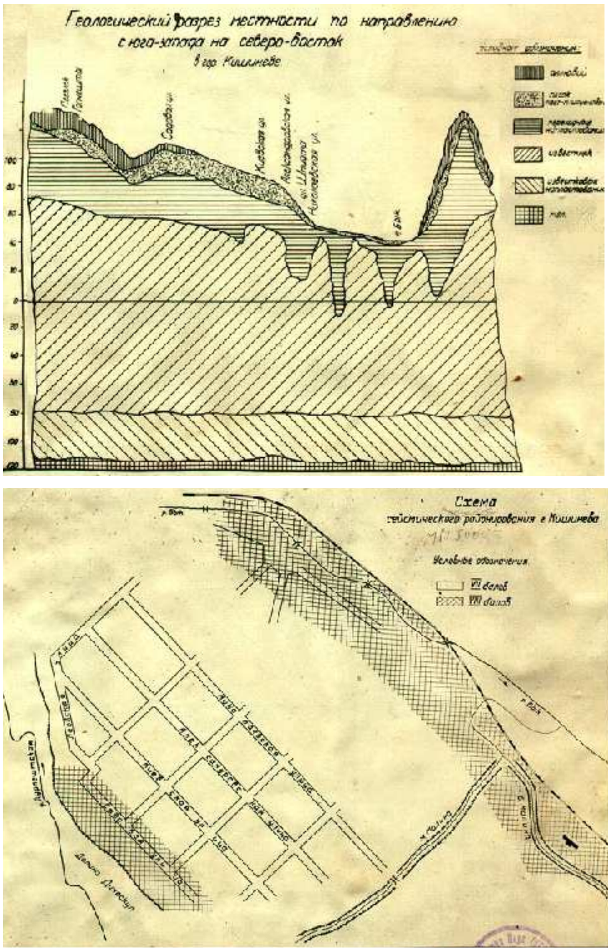


Figure 15. Map of seismic microzonation of Chisinau proposed in 1941 (Tshoher et al., 1941)

Detailed geological and geotechnical data were collected to determine soft soil variations at 1,210 sites.

Based on geological and geotechnical information, lithologically homogenous units for instrument measurements were selected. For each point, the empirical site response was evaluated using different techniques (sediment vs. bedrock ratio, Nakamura's method). Also, a set of analytical amplification functions for horizontal ground motion was computed based on log data and 1-D modeling (Ratnikova, 1984). Validating the results was done with the help of 2-D models (Zahradnik, 1982).

At the majority of the points measured, a satisfactory fit between the empirical and analytical predominant periods and amplification levels was established. The site response spectra exhibited peaks between 0.5 and 8.0 Hz, and the amplification factors ranged from 3 to 7.

The quality of seismic microzonation is basically determined by the degree to which the methodology applied adequately considers the peculiarities of the region. As mentioned in other papers (Alkaz et al. 1996, 2005), the application of microzonation methods based on empirical ratios obtained for shallow earthquakes proves ineffective for the Vrancea region. For intermediate-depth earthquakes, the methodology should include (i) seismic properties of soils for the upper part of the cross-section as well as for larger depths (down to layers with $V_s \geq 1400$ m/s), (ii) a distribution of shear wave velocity with depth, (iii) the quantitative contribution of different soil parameters to seismic effect, (iv) expected response spectra for each intensity zone on the map of microzones. It might be difficult to combine all these requirements in a single seismic microzonation methodology; therefore, we used a set of methods that successfully revised and complemented each other (Table 4).

This combined methodology was applied to seismically microzone the urban area of Chişinău. In addition to drawing the current microzonation map, a set of supplementary maps was developed including a map of the thickness of soft soil deposits, geotechnical and geomorphological maps, a map of soil amplification capacity and a map of the dominant periods of soil (Figure 16a).

The iso-intensity map of microzonation (MSK scale) shows variations in the intensity values between VII and VIII, Figure 16b. According to building code SNiP II-7-81 and the manual *Soil Condition and Seismic Hazard* published in 1988, the microzonation map is helpful in land use planning and aseismic design, in seismic risk assessment and in developing mitigation measures.

3.3.3. Focal Mechanism Solutions for Vrancea Seismic Area

The analysis of focal mechanisms was performed for the region of South-Eastern Carpathians, particularly of the Vrancea zone. The data from the ISC Bulletin for the period 1967-2006 were used in the study, to which the series of supplementary catalogues were added: HVD, M&P, ONC, ANSS, MED, ROM+, SBL, FSU, USGS in order to carry out a thorough complete analysis. As a result the focal mechanisms for about 250 catalogued events were obtained, which were projected on a uniform magnitude scale (M_w) for the geographic area in the limits: Lat. 44-50° and Long. 24-30° for the continuum reference period of 40 years. Uncertainties in the data influencing focal mechanism solutions are discussed.

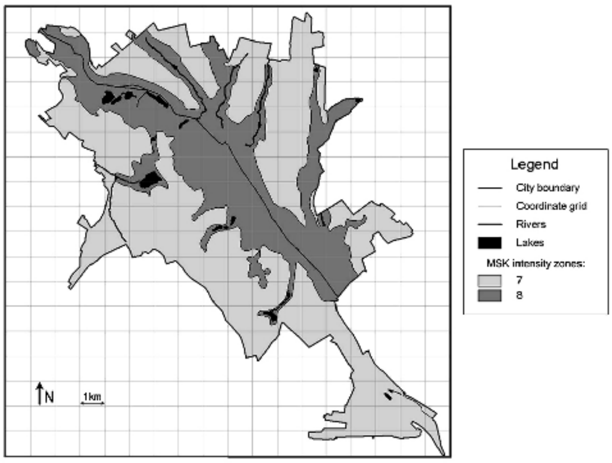
Cataloguing source parameters on a systematic basis revealed the dynamic character of the physical process of mechanical energy release by the source and initiated the study of recurrence intervals of strong events (Steven, 1996; Purcaru, 2003; Popescu et al., 2003). As a result, it has been established that in an average century, Vrancea seismic sources have generated at least 5 strong earthquakes with magnitudes M_w > 6.0 (Wenzel et al., 1999). The same rate of earthquake occurrence was observed in the 20th century with strong events on November 10, 1940, September 7, 1945, March 4, 1977, August 31, 1986 and May 30, 1990 (Engdahl, 2003)

The catalogues of focal mechanisms in the Vrancea zone were compiled from rigorous analyses of the records of strong earthquakes (Trifu and Oncescu, 1987) using polarities of the P-waves, the method used by the authors in the current study and in their recent publications (Sandu and Zaicenco, 2007). Recently, the method of Centroid Moment

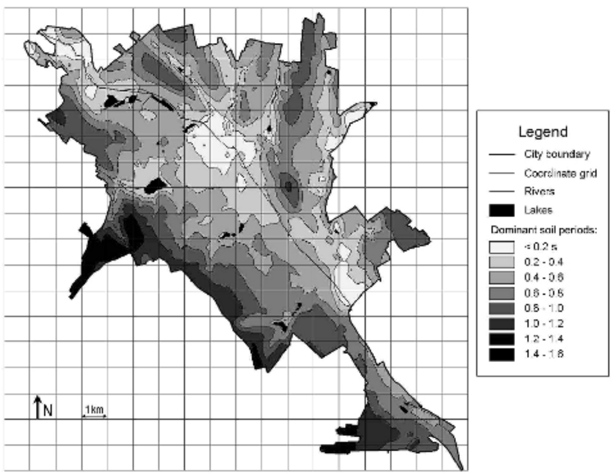
Table 4.

Methodology for Seismic Microzonation

Method	Output
1. Geological and geotechnical studies	Map of geotechnical zonation of territory
2. Instrumental seismological studies: • earthquakes, explosions; • microtremors; • seismic logging: shallow (? 50 m), deep (50-200 m)	increment of seismic intensity Δ*I*; predominant periods of soil vibration velocity V_p, V_s distribution
3. Macroseismic studies	Quantitative contribution Δ*I* of different factors on seismic effect
4. Theoretical methods	a) transfer functions of soils; b) increment of seismic intensity Δ*I* c) influence of surface, internal topography; d) recorded accelerograms (response spectra)



a) Map of dominant periods of soil for the territory of Chisinau



b) Map of seismic microzonation for the territory of Chisinau

Figure 16.

Tensor (Ardeleanu and Radulian, 1998) has been used more frequently due to the advantages offered by digital records (Bala et al., 2003).

The focal mechanism solutions were re-computed using the ISC catalogue and compared the results with already existing solutions (Radulian et al., 1996). A similar effort was undertaken recently in Italy (Pondrelli et al., 2006). In addition to being useful for statistical analysis, this database could demonstrate the complex process of mechanical energy accumulation and release by characterizing the stress-strain distribution within the zone.

The results of the computations are presented in the form of GMT maps (see example in Figure 17).

3.3.4. A Parametric Model Combining Gabor Wavelet and Stochastic Component for the August 30, 1986 Vrancea Earthquake

An analytical model for the representation of strong ground motions is proposed for the August 30, 1986 Vrancea earthquake. The earthquake simulation model is represented by a short-duration, long-period pulse-like function based on the Gabor wavelet, and a long-duration stochastic record that has a frequency content higher than that of the long-period pulse. The simple physical meaning of the input parameters of the model adequately represents the impulsive character of the records, and successful simulation of the entire data set proves the potential of the method for use in ground-motion simulation. The modified Gabor wavelet is capable of capturing the time-history and response spectra characteristics of the coherent component of the records. The incoherent component of ground motion is simulated with the stochastic approach, providing good compatibility of the resulting linear response spectra.

The basic features of the near-field earthquake ground motions are short duration, strong directivity, and low-frequency impulsive motion in the velocity time-history. To adequately represent a coherent signal, which is localized in time, wavelets are employed.

The Gabor wavelet meets the requirements necessary for use in the analytical modeling of seismological signals: it has a simple mathematical expression, it is capable of representing all records in the current study, and it allows the derivation of closed-form expressions of its spectral characteristics (Fourier and response spectra).

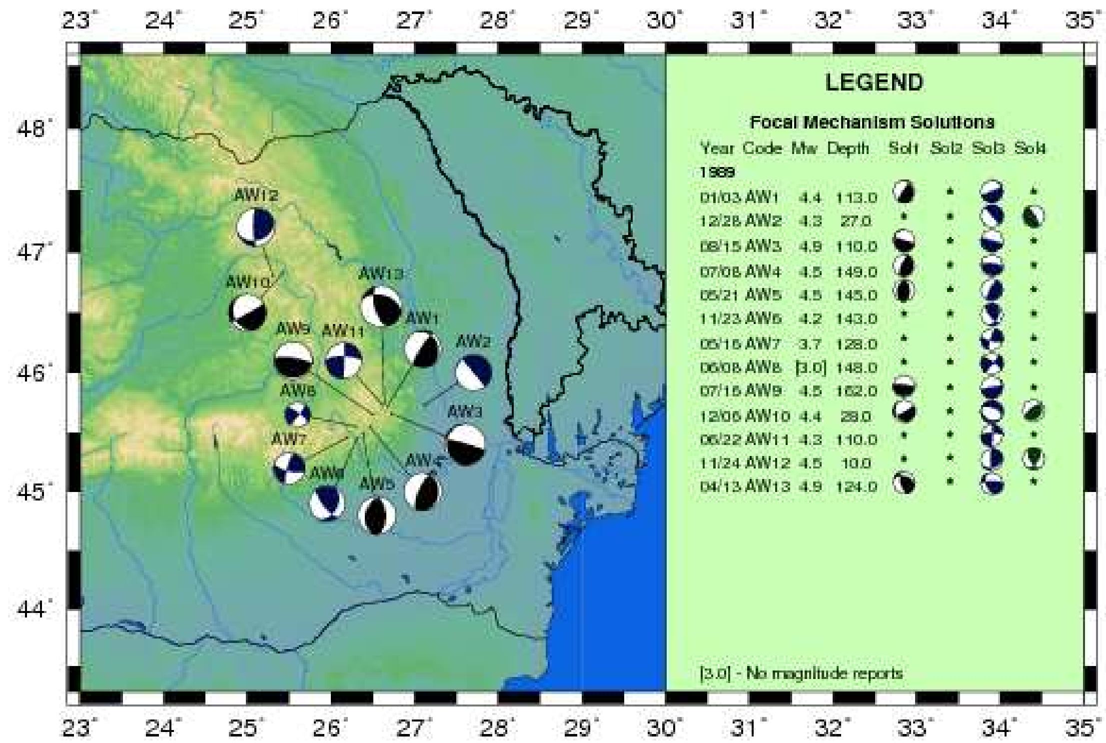


Figure 17. Focal mechanism solution database (extract): year 1989

The records of the August 30, 1986 intermediate-depth Vrancea earthquake clearly demonstrate the “fling”, or velocity pulse, from the radiation mechanism and the directivity of the thrust source. The parameters of the modified Gabor wavelet applied to the records selected show similar features of the low-frequency pulse on all horizontal components that correspond to the second corner frequency of the source spectrum reported from the broad-band records. The incoherent components that are not addressed by the wavelet model, could be considered by the stochastic engineering method. Further research is required to derive the scaling laws for the model parameters, i.e. to investigate the influence of earthquake size on them. As a result, it might be possible to come up with a practical simulation model suitable for engineering aseismic designs from intermediate depth earthquakes for which the near-source recordings remain sparse around the world. The correlation spectra of the peak response statistics of linear SDOF systems with the parameters of the proposed ground-motion model are developed. These spectra allow the degree of influence of the selected model parameters on structural response to be established.

3.3.5. Seismic Risk Study for the City of Chisinau

As part of seismic risk study, European Macroseismic Scale, EMS-92 (Grünthal, 1993) and its building damage classification was applied for damage assessment of the existing buildings in the central part of Chisinau (Figure 19). The vulnerability class *B* (masonry) structures, ≈ 45 % of the total, were selected as the sample space, as providing the most reliable information both from the spatial distribution point of view as well as structural uniformity.

Seismic risk study of Chişinău translated in the map of seismic micro-zonation for the city developed for the Ministry of Construction.

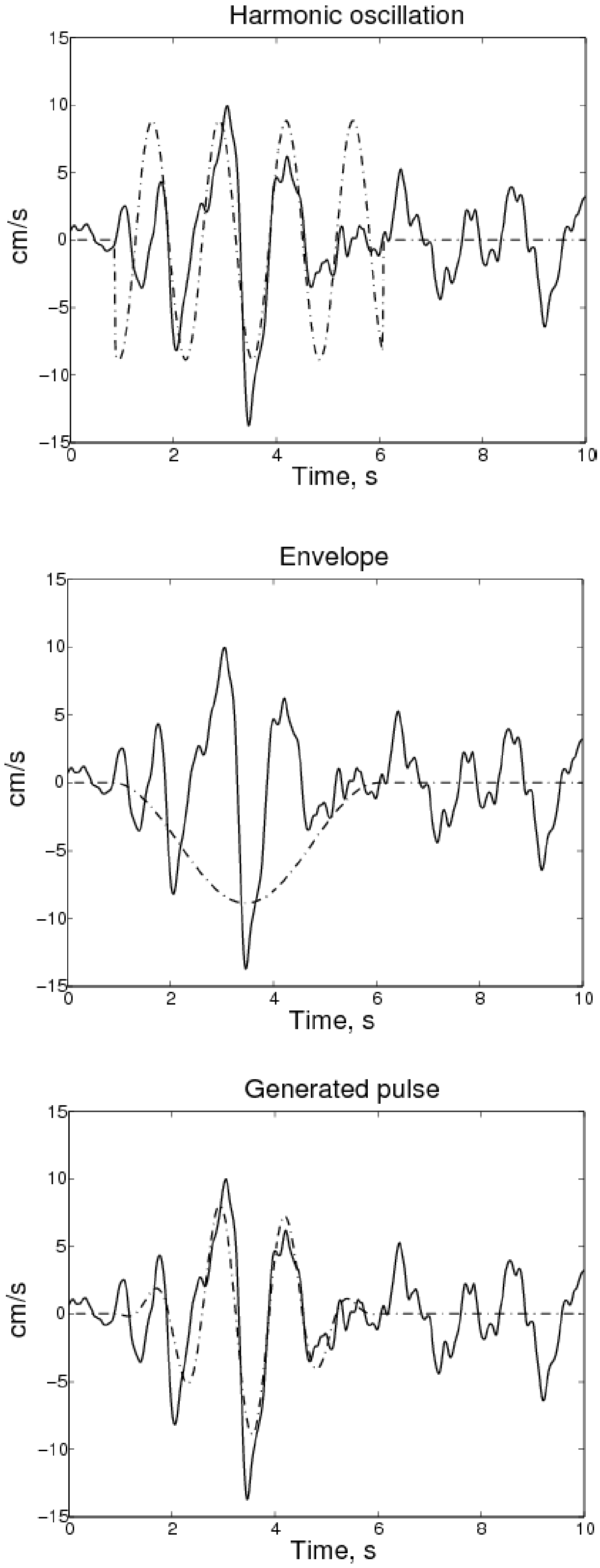
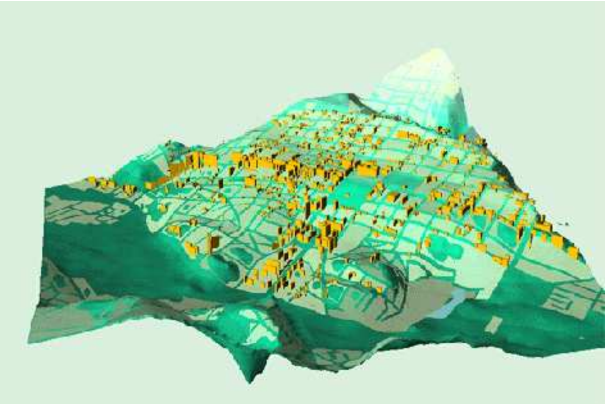
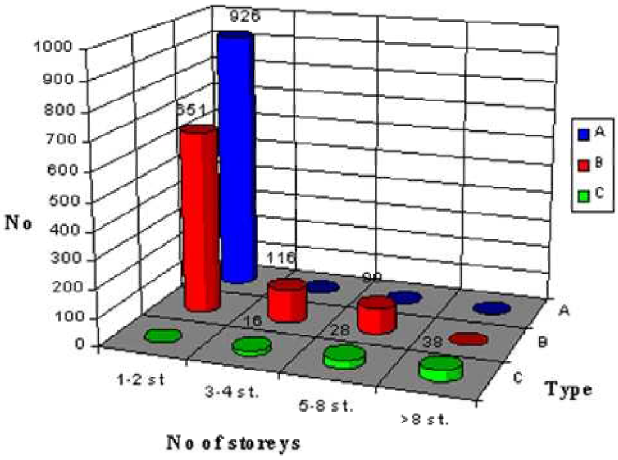


Figure 18. Procedure of fitting Gabor wavelet on BRN N107W component: harmonic oscillation, envelope, fitted pulse



a) GIS model of the central part of Chisinau (2.5 x 2.5 km) showing existing buildings



b) distribution of building types within the studied area (EMS classification)

Figure 19.

Figure 20. MEMS-based data logger

3.3.6. MEMS-Based Data Logger for Seismic Arrays and Structural Health Monitoring

One of the hottest technology growth areas is micro-electromechanical systems (MEMS). According to the market research firm Frost and Sullivan, Mountain View, CA, MEMS is one of a handful of new technologies that could revolutionize the 21st century. The advantage of MEMS for these applications is the relatively low cost and simplicity of the devices. The study presents a MEMS-based data logger designed for seismic arrays and structural health monitoring.

An acceleration data logger incorporating MEMS sensor has recently been designed and built by a team from Moldova (Mohniuc et al, 2008), Figure 20. It might be viewed as a perfect candidate for Class C networks according to the USGS classification. Being a low-power device it operates from AAA-type batteries and is equipped with a GPS sensor. A 16-bit ADC and MEMS sensor from STMicroelectronicsc® allow resolving accelerations at sub milli-g level with a bandwidth of 100 Hz. In early 2008, this data logger was tested against a Guralp CMG-5TD accelerometer on a shake table and demonstrated good performance. Another advantage of this device is its low weight – about 250g.

The compact accelerograph is designed mainly for use in structural health monitoring and nested seismic arrays. Moreover, due to its flexible architecture and compact size, other applications are also possible.

4. CONCLUSIONS

The NATO SfP Project 980468 "Harmonization of Seismic Hazard and Risk Reduction in Countries Influenced by Vrancea Earthquakes" originated from the ideas that the effects of natural hazards, such as earthquakes, are not constrained by borders and that scientists from affected countries should work together in order to mitigate those effects. During the project, these ideas have found multiple paradigms, both in the scientific work itself and in the co-operation relationships that have been established between the project teams in the participating countries.

Some of the major outcomes of the NATO project are:

- Consolidation of the research capacity of the Romanian, Bulgarian and Moldavian project teams, by updating seismic equipment, computational infrastructure, and specialized software;
- Boosting professionalism of the researchers through training;
- Development of significant, internationally validated research results, essential for the progress in the scientific field of the project;
- Higher visibility of seismic research performed by the teams involved, through participation in international symposia, workshops and conferences and by publishing the research results.

ACKNOWLEDGEMENTS

The research reported in this paper was sponsored by NATO's Scientific Affairs Division in the framework of the Science for Peace Programme, project SfP-980468.

REFERENCES

Alkaz ,V., Zaicenco, A., Isiciko, E. (2008), *Seismic Microzonation of Chisinau: a Tool for Reducing Seismic Risk, Harmonization of Seismic Hazard in Vrancea Zone*, Springer, NATO Science for Peace and Security Series - C

Ambraseys, N., Smit, P., Sigbjornsson, R., Suhadolc, P. and Margaris, B. (2002), *Internet Site for European Strong-Motion Data, European Commission, Research-Directorate General, Environment and Climate Programme*

Ardeleanu, L., Radulian, M., *(1998), 21-22 February, 1983 seismic sequences of Ramnicu Sarat: focal mechanism and source time function inferred from short period waveform inversion*, Rev. Roum. Geophys, 47, Bucharest, 27-38

Berrill, J. B., Davis, R. O. (1980), *Maximum entropy and the magnitude distribution*, Bulletin of the Seismological Society of America; 70: 1823-1831

Craifaleanu, I. G. (2005), *Nonlinear Single-Degree-of-Freedom Models in Earthquake Engineering*, Matrix Rom Publishers. Bucharest (in Romanian)

Craifaleanu, I. G., Lungu, D., Borcia, I. S. (2006), *Shakemaps of Nonlinear Spectral Ordinates for Vrancea Earthquakes*, Proceedings of the First European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland, 3-8 September, Paper No.1257 (on CD-ROM)

Craifaleanu, I. G. (2007), *An Assessment of the Damage Potential of Romanian Vrancea Earthquakes*, Proceedings of the International Symposium on Strong Vrancea Earthquakes and Risk Mitigation, Bucharest, Oct. 4-6, pp. 317-327, Matrix Rom Eds., Bucharest

Craifaleanu, I. G. (2008a), *An Assessment of Damage Potential and Building Performance Demands for Romanian Vrancea Earthquakes, Harmonization of Seismic Hazard in Vrancea Zone with Special Emphasis on Seismic Risk Reduction*, Proceedings of the NATO Science for Peace Project on Harmonization of Seismic Hazard and Risk Reduction in Countries Influenced by Vrancea Earthquakes Chisinau, Moldova 20 May 2008, Zaicenco, A.; Craifaleanu, I.; Paskaleva, I. (Eds.), Springer

Craifaleanu, I. G. (2008b), *A Comparison Between the Requirements of Present and Former Romanian Seismic Design Codes*, Based on the Required Structural Overstrength, Proc. 14WCEE, paper No. 08-01-0035 (on CD-ROM)

Dong W. M., Bao A. B. and Shah H. C. (1984), *Use of maximum entropy principle in earthquake recurrence relationships*, Bull. Seism. Soc. Am., V.74, pp.725-737

Dziewonsky, A. M., Ekstrom, G., Woodhouse, J. H., Zwart, G. (1991), *Centroid moment tensor solutions for April-June 1990*, Physics of the Earth and Planetary Interiors, 66, 133 - 143

Engdahl, E. R. (2003). Global Seismicity: 1900-1999, *International Handbook of Earthquake and Engineering Seismology*, 81A, 665-690

Ginsari, V. (2008), *Estimation of the recurrence and probability of Vrancea intermediate depth earthquakes, Harmonization of Seismic Hazard in Vrancea Zone*, Springer, NATO Science for Peace and Security Series – C

Global Seismic Hazard Assessment Programme, Annali di Geofisica, V. XXXVI, No 3-4, 1993

Gutenberg B. and Richter C.F. (1956), *Magnitude and energy of earthquakes*, Ann. geophys., v.9, N1, 1-15

Gruenthal G. (1993), *European Macroseismic Scale 1992 (updated M.S.K. scale)*, Conseil de l'Europe, Cahiers du Centre Europeen de Geodynamique et de Seismologie, Vol.7, 79, Luxembourg

Hwang, H. H. M., Huo, J. R. (1994), *Generation of hazard-consistent fragility curves for seismic loss estimation studies*, Technical Report NCEER-94-0015, National Center for Earthquake Engineering Research, State University of New-York at Buffalo, USA

Kouteva-Guentcheva, M.P., Paskaleva, I. P., Panza, G.F. (2008a), *Strong Intermediate-Depth Vrancea Earthquakes: Damage Capacity in Bulgaria*, 14WCEE, October 12-17, Beijing China, Ref. 07-0050

Kouteva, M. and Paskaleva I. (2008b), *Seismic Monitoring: a Contribution to the Sustainable Development of the Russe Region of Bulgaria, In: Harmonization of Seismic Hazard in Vrancea Zone with Special Emphasis on Seismic Risk reduction*, Editors: A. Zaicenco. I. Craifalenu, I. Paskaleva, NATO Science for Peace and Security Series-C: Env. Security, Springer, pp.183-197

Kouteva-Guentcheva, M., Paskaleva I., Panza G. F. (2008c), *Earthquake Source and Local Geology Effects on the Seismic Site Response In: Site Effects and Soil Structure Interaction*, NATO ARW, Editors: T. Shanz and R. Iankov, Springer (in Print)

Lungu, D., Aldea, A., Demetriu, S., Craifaleanu, I. (2004), *Seismic strengthening of buildings and seismic instrumentation -two priorities for seismic risk reduction in Romania*, CD, 1st Int. Conf. Science and Technology for Safe Development of Lifeline Systems, Natural Risks: Developments, Tools and Techniques in the CEI Area

Lungu, D., Craifaleanu, I. G. (2007), S*patial Distribution of Strength and Displacement Demands for Romanian Earthquakes, Proceedings of the International Symposium on Seismic Risk Reduction*, The JICA Technical Cooperation Project in Romania, Bucharest, April 26-27, pp. 407-412, Paper ID: 79

Lungu D., Craifaleanu I.-G. (2008), *Shake Maps of Strength and Displacement Demands for Romanian Vrancea Earthquakes*, Proceedings of the 14WCEE, Beijing, China, Oct. 12-17, Paper No. 03-03-0060 (on CD-ROM)

Mohniuc, R., Zaicenco, A., Kuendig C., Kurmann T. (2008) 4.9. 4.10. *MEMS-based Data Logger for Seismic Arrays and Structural Health Monitoring, Harmonization of Seismic Hazard in Vrancea Zone*, NATO Science for Peace and Security, Series-C, Springer

Nenov, D., Paskaleva, I., Georgiev, G., Trifunac, M. (1990) C*ATALOG of strong earthquake ground motion data in EQINFOS: Accelerograms recorded in Bulgaria between 1981 and 1987*, Report No CE 90-02, Sofia and Los Angeles, 1990, 55 pages, published in Southern California University

Panza, G.F., Romanelli, F., Vaccari F. (2001), *Seismic Wave Propagation in Laterally Heterogeneous Anelastic media: theory and applications to the seismic zonation*, Advances in Geophysics, Academic press; 43, pp. 1-95

Paskaleva, I., Kouteva, M. (2007), *Intermediate Progress Report*, NATO SfP Project 980468, CLSMEE - Bulgarian Acad. Sci.

Paskaleva, I., Kouteva, M., Vaccari F., Panza G. F. (2008), *Application of the Neo-Deterministic Seismic Microzonation Procedure in Bulgaria and Validation of the Seismic Input Against Eurocode 8*, Proc. of 2008 Seismic Eng. Conf. commeorating the 1908 Messina and Reggio Calabria Earthquake, Reggio Calabria, Italy, 8-11 July, 2008, Part one, Editors: A. Santini and N. Moraci, American Institute of Physics, AIP Conference Proc. 1020, pp. 394-402

Pondrelli, S., Salimbeni, S., Ekstrom, G., Morelli, A., Gasperini, P., and Vannucci, G. (2006), *The Italian CMT dataset from 1977 to the present*, Phys. Earth Planet. Int., 159,3-4, 286–303

Purcaru, G. (1979), T*he Vrancea, Romania, earthquake of March 4, 1977 – a quite successful prediction*, Physics of the Earth and Planetary Interiors, 18, 274-287

Radu C. (1982.), *Catalogul cutremurelor puternice produse pe teritoriul României. Partea I, II. În: Cutremurul de pămînt din România de la 4 martie 1977*. Ed. Academiei Române, Bucureşti, 1982, 78-85

Radu C. (2003), *Catalogul istoric al cutremurelor din Vrancea în perioada 984-1900. În: Construcţii amplasate în zone cu mişcări seismice puternice*, Ed. Orizonturi Universitare, Timişoara, p.25.

Radulian, M., Mindrescu, N., Popescu, E., Utale, A., Panza, G. F. (1996), *Seismic Activity and Stress Field Characteristics for the Seismogenic Zones of Romania*, International Center for Theoretical Physiscs, Miramare-Trieste, December, IC/96/256

Radulian, M., Vaccari, F., Mandrescu, N., Panza, G.F., Moldoveanu, C. (2000), *Seismic Hazard of Romania: Deterministic Approach*, PAGEOPH, Vol.157, no1/2, 221-247.

Ratnikova, L. I., *Computation of oscillations at the free surface and internal points of horizontally layered damped soil*. In: Seismic microzoning, M., Nauka, 1984, 235 p (in Russian).

Sandu, I., Zaicenco, A. (2007), F*ocal Mechanism Solution Catalogue for SE Carpathian Region*, Thirty Years from the Romania Earthquake of March 4, 1977, Bucharest, Romania.

Sandu, I., Zaicenco, A. (2008), F*ocal Mechanism Solutions for Vrancea Seismic Area, Harmonization of Seismic Hazard in Vrancea Zone*, Springer, NATO Science for Peace and Security Series – C

Steven, L. K. (1996), *Geotechnical Earthquake Engineering, Prentice-Hall Civil Engineering and Engineering Mechanics Series*

Trifu, C., Oncescu, M. (1987), *Fault geometry of August 30, 1986 Vrancea earthquake*, Ann. Geophys., 5B, 727-729.

Tshoher, V., Tischenko, V. (1941), *Report "The Carpathian Earthquakes of October, 22 and November, 10, 1940"*, Archives of the Institute of Geology and Seismology, Academy of Schences, Republic of Moldova (in Russian).

Wenzel, F., Lorentz, F. P., Sperner B., Oncescu M.C., (1999). *Seismotectonics of the Romanian Vrancea Area.* In: Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation, 15-25, Wenzel et al. (eds.), Kluwer Academic Publishers.

Zahradnik, J. (1982), *Seismic response analysis of two-dimensional absorbing structures*, Stud. Geophys. and Geod., vol.26, pp.24-41

Zaicenco, A., Gavin, H. P., Dickinson, B. W. (2008), *A Parametric Model Combining Gabor Wavelet and Stochastic Component for the August 30, 1986 Vrancea Earthquake, Harmonization of Seismic Hazard in Vrancea Zone*, Springer, NATO Science for Peace and Security Series - C

CEN (2004). *Eurocode 8: Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings, EN 1998-1. European Committee for Standardization*

Code for Design of Structures in Seismic Regions (1987), Sofia, Bulgaria.

MTCT (2006), *Seismic Design Code – P100. Part I – P100-1/2006: Design Rules for Buildings*, Ministry of Transport, Constructions and Tourism, Construction Bulletin. 12-13, edited by INCERC (in Romanian)

MLPAT (1992), *Code for the Seismic Design of Residential, Agricultural and Industrial Structures – P100-92*, Ministry of Public Works and Regional Planning, Construction Bulletin. 1-2-3, edited by INCERC (in Romanian)