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DISSERTATION - ABSTRACT

MODELLING, ANALYSIS AND ASSESSMENT OF THE SEISMIC EFFECTS OF THE VRANCEA EARTHQUAKES ON THE BULGARIAN TERRITORY

Code 010204 – „Mechanics of Deformable Solids”

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Sofia, 2012

Acknowledgements:

I would like to express my deep gratitude to my family for their support and patience, and for all the time that I have stolen from them.

I would like to express my deep gratitude to my consultants Assoc. Prof. I. Paskaleva and Prof. G. F. Panza for their always open doors for me, for the fruitful collaboration and their support during the work on this thesis, and for all of the drawn horizons for further research.

I highly appreciate the support of the managing and executive bodies of the Department of Earthquake Engineering and the National Institute of Geophysics, Geodesy and Geography, NIGGG-BAS concerning the planning, organization and execution of my scientific and educational PhD program, as well as for the organization of the administrative procedures.

I am deeply grateful to all my colleagues for their constructive comments, notes and professional advices.

I would like to express my sincere gratitude to the Members of the Scientific Jury for their time and for all notes, comments, advices and constructive criticism, expressed in the reviews.

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1. INTRODUCTION. ACTUALITY OF THE POSED PROBLEM OF MODELLING, ANALYSIS AND ASSESSMENT OF THE SEISMIC EFFECT OF THE VRANCEA EARTHQUAKES ON THE BULGARIAN TERRITORY.

Over the centuries, Bulgaria has experienced strong earthquakes. The seismicity of neighboring areas in Greece, Turkey, the former Yugoslavia and Romania, especially Vrancea intermediate-depth earthquakes, contributes significantly to the seismic hazard in Bulgaria. The total area affected by intermediate-depth Vrancea earthquakes comprises 300,000 square kilometers ($km^{2)}$ with a population of about 25 million people [Zaicenco and Alkaz 2005]. The maximum observed macro seismic intensity in the Vrancea intermediate zone has reached intensity (I) ~VIII-IX MSK-64. A special feature of the Vrancea earthquake hazard in Bulgaria is its irregular macro seismic effects. In all cases, southwest to northeast bands of maximum seismic effect were traced [Glavcheva 1983]. The area that has suffered damage of severity I~VI (severe ground motion and building damage) includes Romania, Moldova, a large part of Bulgaria and southwestern Ukraine. A number of important cities, numerous industrial and energy facilities (including two nuclear power plants), industrial chemical facilities, lifelines of crucial importance (railways, gas and fuel pipelines, bridges and dams) are situated in this earthquake-prone area. The four strongest earthquakes (Mw>6) that occurred in the Vrancea zone during the last century (in 1908, 1940, 1977, 1986 and 1990) caused significant damage over a wide part of Europe including distant, long-period elements in the built environment. The quake of March 4, 1977, (M_W=7.5) caused significant damage in Bulgaria and was felt in Central Europe at distances of about 1,000 km.

The strong, irregular but not infrequent manifestations of the Vrancea focus (70 to 170 km) have always affected Bulgaria. They have caused a high death and injury toll and extensive damage over the last several centuries. The wave field radiated by Vrancea intermediate-depth earthquakes mainly at long periods (T>1 s) attenuates with distance less rapidly than the wave fields of earthquakes in other seismically active zones in Bulgaria. Vrancea intermediate-depth earthquakes are thus the dominant hazard in large parts of northern Bulgaria; an appropriate understanding of these earthquakes is of great importance for adequate hazard assessments [Paskaleva et al. 2004; Simeonova et al. 2006].

The built stock, all structures, lifelines and other infrastructure, which are built on the Bulgarian territory, are very often exposed to the impact of different earthquake sources, located in the Bulgarian territory as well as in the territory of the neighboring countries [Paskaleva et al., 2001; Simeonova et al., 2006]. The earthquake record, starting from the year 536 to nowadays, has shown nine strong earthquakes M_s >= 6.0 [Hristoskov, 2005 a, b] that are shallow crustal seismic event with focal depth up to 60 km. Sixty four strong Vrancea earthquakes were registered during the last 200 years; eight of these quakes caused significant damages in Bulgaria. These quakes are of a great scientific, scientific – applied and social-economic interest since the impact of a major Vrancea intermediate-depth earthquake may produce strong direct damage, as well as indirect losses in other regions of the country, thus leading to a national disaster.

The Vrancea subduction seismogenic zone is a peculiar intermediate-depth source with the following features:

- The seismicity is concentrated in a relatively narrow focal volume, limited between depths of 60 to 200 km, characterized by high velocities of seismic waves propagation and continuous release of seismic energy [Raykova and Panza, 2006]; the frequency-amplitude characteristics of the intermediate-depth earthquakes differ significantly from the shallow ones [Gusev et al., 2002];
- The major Vrancea earthquakes are characterized by a reverse faulting mechanism with T-axis almost vertical and P-axis almost horizontal The fault plane orientations can be divided in two main groups oriented on (1) NE-SW – e.g. the earthquakes of March 4, 1977 (VR77); August 30, 1986 (VR86) and (2) NW-SE direction, e.g. May 31, 1990 [Moldoveanu et al., 2001; Gusev et al., 2002];
- The strongest quakes radiate predominantly long-period seismic waves in the frequency range 0 - 1 Hz [Gusev et al., 2002], and the velocity attenuation of these waves is strongly dependent on the frequency content of the seismic signals.

The major objectives of this study are to perform:

- ***critical comparative analysis of the contemporary methods for modelling of the seismic wave propagation in heterogeneous geological medium and of the available geological, geophysical and seismological information;***
- ***modelling and provide prognostic assessment of the expected seismic loading on the building and infrastructure, located within the Bulgarian territory, following given seismic scenarios for the peculiar Vrancea earthquakes.***

2. STATE OF THE ART – THE IMPACT OF THE VRANCEA EARTHQUAKES IN BULGARIA

The scientific interest, relevant to the Vrancea seismic zone, has been mainly oriented to: (a) analysis of the available macro seismic and instrumental geophysical and seismological data and (b) theoretical modeling of the seismic excitation, caused by the seismic sources, located in this zone. The increased interest of the scientific society to the Vrancea earthquakes during the last ten years was the engine of several international research projects: NATO SFP 981882, NATO ENVIR.LG.960916, NATO SfP 980468; UNESCO.IUGS.IGCP 414; FP-7 Contract nr.52566/05.08.2010-2013 (DACEA); CEI projects no. 1202.001-07, 1202.136-07, 1202.038-09. Among the numerous publications we can distinguish two interesting problem oriented monographies: (1) The Vrancea Earthquakes: Tectonics and Seismic Hazard and Risk Mitigation [A.A V.V. 1999] и (2) Topical Volume of Pure and Applied Geophysics (PAGEOPH) titled Seismic Hazard Assessment of the Circum-Panonian Region" [A.A V.V, 2000].

The XX century is characterized by the highest seismic activity of the Vrancea seismic zone. The earthquake record has shown about 100 strong Vrancea earthquakes M_w > 5.0, registered in Bulgaria. Isoseismic maps for 40 of these events are published in 1983 [Rizhikova, 1983]. Focal depths and macro seismic intensities MSK of the strongest Vrancea earthquakes are given in Table 1 [Lungu et al., 1999; Alkaz, 2005]. The 1977 earthquake caused significant losses in Bulgaria, more than 10 000 residential buildings in Russe and Russe region were damaged [A.A V.V, 1983a]. The last strong Vrancea earthquakes (M_w > 6.0) are the August 30, 1986 and May 30-31, 1990 earthquakes.

Table 1. Strong intermediate-depth Vrancea earthquakes (M > 7.0) [Lungu et al., 2004; Alkaz, 2005*, **].

Earthquake	Epicentral Intensity I_o	Focal Depth, km	Magnitude M_w	Intensity NE Bulgaria *(Russe)*	Note
*1802, 26 October **	*> IX*	-	*7.9* *8.1**	No data	**1802 the strongest occurred Vrancea earthquake*
1829, 20 November	VIII	-	-	VII	
1838, 23 January	VIII	-	-	VII	
1940, 10 November	IX	150	7.7	VII	
*1977, 4 March***	*VIII - IX*	*109*	*7.5*	*VII - VIII*	***1977 the heaviest damages*
1986, 30 August	VII - VIII	133	7.2	IV – V	

2.1. Instrumental data – recorded accelerograms of the strong Vrancea earthquakes

Accelerograms due to Vrancea intermediate-depth earthquakes have been recorded on three seismic networks in Romania as well as on the seismic networks of the Academy of Science in Moldova and the Academy of Science in Bulgaria. The instrumental earthquake record in Bulgaria dates from 1981. Earthquake catalogue of the strong Bulgarian earthquakes was published in 1990 [Nenov et al. 1990]. The number of the horizontal accelerograms that were recorded due the strong Vrancea earthquakes is given in Table 2. So far, two strong Vrancea earthquakes have been recorded in Bulgaria – five accelerograms components due to the Vrancea quakes of 30.08.1986 (VR86) and 30.05.1990 (VR901) were recorded at Russe station.

Table 2. Instrumentally recorded accelerograms due to Vrancea earthquakes [Ambraseys et al., 2002*, Nenov et al., 1990 **].

Earthquake	Magnitude Mw	Focal Depth, H, km	Number of the registr. stations	Number of the recorded horizontal components
1977, 4 March	7.4	90	3*	6*
1986, 30 August	7.2	133	11*	22*
1990, 30 May	6.9	74	14*	28*
		+/-6 (16)	2**	3**
1990, 31 May	6.2	90	8*	16*

Comparison of the dynamic coefficients of the recorded accelerograms, listed in Table 2 is shown in figures 1-2. The similar shape of the spectral curves, shown in these figures, indicate that the significant influence of the kinematics of the Vrancea seismic source on the seismic loading that is generated by this source.

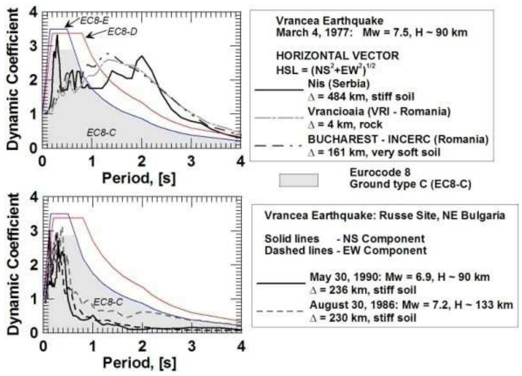


Figure 1. Plots of the dynamic coefficients, computed for the records of the strong intermediate-depth Vrancea earthquakes and the relevant Eurocode 8 curves for soil type C, D and E. Up: March 4, 1977 - Nis (Serbia), Vrancioaia and Bucharest (Romania); Down: August 30, 1986 and May 30, 1990 – Russe (Bulgaria).

2.2. Theoretical estimates and analyses

The published theoretical studies on the Vrancea earthquakes and their impact are mainly focused on the regional seismic hazard assessment [Panza & Vaccari, 2000] or concern particular countries [Radulian et al., 2000; Simeonova et al., 2006]. Todorovska and Paskaleva published some results concerning the generated uniform spectra for the site of Russe [Todorovska et al, 1995], but in the scientific literature, published before 2000 there are not publications on the alternative representation of the seismic loading, due to the strong Vrancea earthquakes.

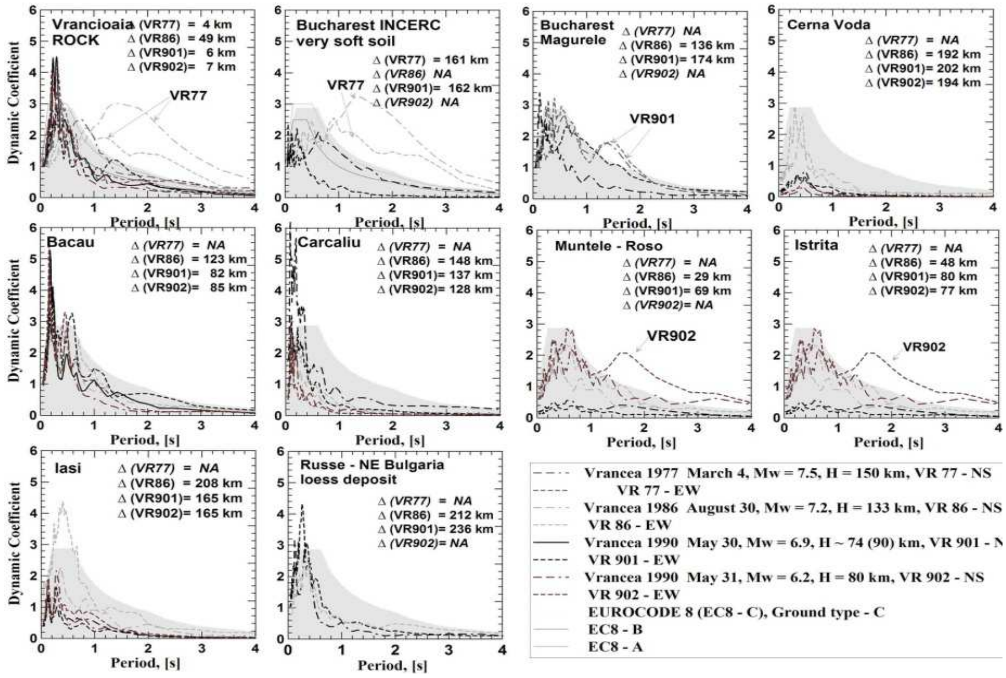


Figure 2. Plots of the dynamic coefficients, computed for the records of the strong intermediate-depth Vrancea earthquakes [Ambraseys et al., 2002; Nenov et al., 1990] and the relevant Eurocode 8 curves for soil type C, D and E.

2. Engineering Analysis of the Data that are Recorded within the Period 1983 -2012, Related to the Damage Potential of Strong Intermediate-Depth Vrancea Earthquakes

2.1. Parameters Related to the Earthquake Damage Potential

The available records of the strong ground motion due to the intermediate depth Vrancea earthquakes [Nenov et al., 1990; Ambraseys et al., 2002] have been analyzed with regard to the peak and integral parameters [Cosenza & Manfredi, 2000]. The ***Peak Parameters*** include the Peak Ground Acceleration, (PGA), the Peak Ground Velocity, PGV, the Peak Ground Displacement, PGD, and some ratios as PGV/PGA and PGD/PGV. Historically, the most used parameter in the engineering analysis for the characterization of the seismic hazard is the Peak Ground Acceleration, PGA. The PGA is a basic measure of earthquake potential, it is relatively easy to determine, but it might lead often to wrong seismic risk estimates. Other peak parameters that are used to characterize the ground motion are the Peak Ground Velocity, PGV, the Peak Ground Displacement, PGD, and some ratios as PGV/PGA and PGD/PGV. The PGV is considered to be a more representative measure of earthquake intensity, directly connected with energy demand. Different authors assume the peak motion ratio PGV/PGA as a measure of destructiveness. Actually, the peak values alone, as single-value indicators, cannot describe adequately all the effects associated to the ground shaking, since the duration of a seismic wave train and the frequency content play a fundamental role [Cosenza & Manfredi, 2000].

The ***Integral Parameters*** are much more effective for measuring the energy content of a seismic event. They are defined as the root mean square acceleration (RMSA), velocity (RMSV) and displacement (RMSD), $RMSX = \sqrt{\frac{1}{t_r}\int_0^t [x(t)]^2\, dt}$ where x (t) is either the ground acceleration a_g (t), velocity v_g (t) or displacement d_g (t) and t_E is the total duration of the earthquake. The Arias intensity I_A [Arias, 1970], based on the RMSA can be related to energy content. The damage factor, I_D, proposed by Cosenza and Manfredi [2000] is related to the number of plastic cycles, n, and therefore, to the energy content of the earthquake. All these integral measures depend upon the duration of the earthquake which is a measure that cannot be predicted with any certainty.

Other representative characteristics of the ground motion are connected with the spectral amplitudes of the response acceleration, velocity and displacement spectra SA, SV and SD, the fundamental period T and the dynamic coefficient β, defined as the ratio $\beta = SA/PGA$.

3.1. Data processing and analysis

So far, 52 accelerograms components (31 horizontal и 21 vertical) due to the last four strong Vrancea quakes 30.08.1986 (VR86), 30.05.1990 (VR901) and 31.05.1990 (VR902), from all 123 recorded Vrancea accelerograms, are analyzed. Summary of these components is shown in Table 3. *PGA, PGV, PGA/PGV,* I_A, I_D, T_P, SA_{max} *(5%) and* $\beta = SA/PGA$ are computed for all these components.

Table 3. Registration stations and relevant processed components

Registration stations				*Number of processed components*			*Earthquake*
No	Abbr.	Latitude °E	Longitude °N	*Hor.*	*Vert.*	*all*	
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1	*Nis*	23.901	43.305	*6*	*3*	*9*	*VR77*
2	*INCERC*	26.161	44.441	*6*	*3*	*9*	*VR77*
3	*VRI*	26.727	45.866	*8*	*3*	*11*	*VR77, VR86, VR901, VR902*
4	*BAC*	26.900	46.567	*6*	*3*	*9*	*VR86, VR901, VR902*
5	*CER*	28.032	44.314	*6*	*3*	*9*	*VR86, VR901, VR902*
6	*CCR*	28.136	45.178	*6*	*3*	*9*	*VR86, VR901, VR902*
7	*ISR*	26.545	45.138	*6*	*3*	*9*	*VR86, VR901, VR902*
8	*Pyce*	26.010	43.860	*3*	*2*	*5*	*VR86, VR901*

The obtained results and the computed values of the chosen parameters for the horizontal components, e.g. 0.06<PGV/PGA<0.30 (0.69) are comparable with relevant values, computed for strong earthquakes, such as Kobe, 1995 (M_w=6.9, 0.06<PGV/PGA<0.17), Chichi, 1999 (M_w=7.6, 0.06 <PGV/PGA< 0.40 (0.7)) and Wenchuan, 2008 (M_w=7.9, 0.05<PGV/PGA<0.16) [Cosenza and Manfredi, 2000; Lew, 2008; http://peer.berkeley.edu/svbin/GeneralSearch].

The example of the Vrancea 1977 earthquake is among the most illustrative examples for the typical features of the strong (M_w > 7.0) intermediate-depth Vrancea quakes: (a) the significant influence of the source mechanism on the seismic loading at a given site as compared to the contribution of the local geology to the ground motion at the site; (b) the periods, corresponding to the maximum response spectral accelerations at the recording sites indicate the long period component of the seismic loading due to these earthquakes. The dynamic amplification (β) of the vertical ground motion component is comparable with the relevant values, obtained for the horizontal components, but the absolute values of the response acceleration spectra amplitudes are significantly smaller than the relevant values for the horizontal components. For this reason this study deals further only with the horizontal ground motion components.

The analysis of the available accelerograms (time histories and spectral characteristics), recorded due to the VR77, VR86, VR901 and VR902 has shown clearly the azimuthal dependence of the parameters, relevant to the damage potential of the ground motion [Kouteva, 2010]. The computed values of the damage index I_D^{VR77} ~ 13.5, I_D^{VR86} ~ 17, I_D^{VR901} ~ 15 и I_D^{VR902} ~ 17 are comparable with those, obtained for the Montenegro, M_w = 7.1, 1979 (I_D = 15.35), Chile, M_w = 8.1, 1985 (I_D = 35.84), Mexico, Mw = 8.1, 1985 (I_D = 35.84) and Cobe, M_w = 6.9, 1995 (I_D = 6.91) earthquakes [Cosenza & Manfredi, 2000].

4. Choice of Method for Modelling of the Seismic Loading due to the Vrancea Sources Based on the Contemporary Methods for Alternative Methods for Seismic Loading Representation.

Common practice is to define the seismic loading using equivalent static forces using the spectral curves, given in the legislation. Different possibilities when the seismic loading has to be modeled as acceleration time histories (accelerograms), which differs significantly from the common case, are discussed in the Eurocode 8, Part 1, and p.3.2.3. (BDS EN 1998-1:2005; EN 1998-1:2004). Such definition of the seismic loading is also necessary for the purposes of dynamic analysis of special structures (NPP, dams, and lifelines). The contemporary engineering practice proposes two ways for definition of the seismic loading as accelerograms: (a) **recorded time history** of real seismic event, which occurred in the same region or in a region with similar tectonics and geology and (b) ***theoretically computed seismic signal*** for the site of interest.

4.1. Recorded time histories

Using recorded time histories it is necessary to perform particular scaling of the recorded data that aims normalization of the representative ground motion components of the recorded seismic events by amplitudes and time scale. To provide reliable results using this method we need a representative data base of recorded seismic events. The lack of enough instrumentally recorded time histories of strong ground motions is among the major engines of the elaboration of different methods for theoretical computing of seismic signals, taking into account the seismic source and the geological properties of the seismic waves propagation paths.

4.2. Theoretically generated accelerograms

Different approaches are used to estimate these parameters: stochastic, probabilistic and deterministic. These methods are based on different assumptions and use different approximations and models. One of the most widely methods used for seismic loading definition are based on the probabilistic hazard assessment. The seismic hazard evaluation, which is based on the traditional Probabilistic Seismic Hazard Analysis (PSHA), relies on the probabilistic analysis of earthquake catalogues and of ground motion, macro seismic observations and instrumental recordings. Recently PSHA showed its limitation in providing a reliable seismic hazard assessment, possibly due to insufficient information about historical seismicity, which can introduce relevant errors in the purely statistical approach mainly based on the seismic history. The comparison between the observed peak ground accelerations (PGA) and the PGA predicted by PSHA (the GSHAP Project) for the recent examples of the Kobe, 17.1.1995; Bhuj, 26.1.2001; Boumerdes, 21.5.2003, Bam, 26.12.2003, Wenchuan - China 2008, Japan, 2011 and Italy, 2012 has shown significant disagreement [2]. The probabilistic map, for the 475 years return period, gives a maximum PGA in the range 0.6-0.8 g, centered on the Vrancea region (GSHAP). Observations clearly indicate that Vrancea sits on a relative minimum.

Recent discussions on the traditionally used probabilistic and deterministic seismic hazard assessment approaches, PSHA and DSHA [Klügel et al., 2006; Klügel, 2007; Panza et al., 2008], have shown some major advantages of the scenario based neo-deterministic seismic hazard assessment approach (NDSHA). The scenario-based methodology is strictly based on observable facts and data and complemented by physical modelling techniques, which can be submitted to a formalized validation process. Knowledge gaps related to lack of data can be dealt with easily by means of sensitivity analysis [Klügel, 2007; Panza et al., 2008]. The NDSHA procedure provides strong ground motion parameters based on the seismic wave propagation modelling at different scales - regional, national and metropolitan. The current world practice is more and more targeted on elaboration and use of hybrid methods that combines the advantages of the different methods with the major aim for realistic reliable modeling of the seismic input. Brief comparison between the DSHA, PSHA and NDSHA is given in Table 4.

Table 4. Summary of the discussed seismic hazard assessment procedures, PSHA, DSHA and NDSHA [Panza, Kouteva et al., 2008]

Procedure description	PSHA	DSHA	NDSHA
Step 1		**Seismic sources** Identification of Seismogenic Zones and Capable Faults; Epicenters; Geometry and Focal mechanism;	
Step 2	**Recurrence rate** can be represented by a linear relation only if the size of the study area is large with respect to linear dimensions of sources.	**Fixed magnitude** **Fixed distance** **Choice of the Controlling Earthquake**	**Scenario Earthquakes** – fixed magnitudes, distances and specific seismic source properties. **Choice of the Controlling Earthquake**
Step 3	**Attenuation relations -** they represent the functional dependency of the random spectral acceleration on the random variables, magnitude, distance and measurement error [3] and thus are source of systematic error in the seismic hazard assessment		**Synthetic ground motions.** **NO NEED OF ATTENUATION RELATIONS.**
Step 4	**Seismic hazard assessment in terms of *Probability of exceedance of a given ground motion measure***	**Seismic hazard assessment in terms of *Fixed Ground Motion Measure***	**Seismic hazard assessment *Envelopes of PGA or other Ground Motion Measure***

5. Brief Description of the Neo-Deterministic Procedure for Modelling of the Seismic Wave Propagation in Heterogeneous Geological Medium.

The described Neo-Deterministic Procedure for ground motion modelling is capable to incorporate the effects of lateral heterogeneities in the direct modelling of the wavefield, in order to retrieve a correct image of the heterogeneity itself and consequently to understand the geodynamics of the studied portion of the Earth. This theoretical approach, elaborated at the University of Trieste and SAND – ICTP, Trieste, is based on computer codes, developed from a detailed knowledge of the seismic source process and of the propagation of seismic waves, can simulate the ground motion associated with the given earthquake scenario.

5.1. The wave equation.

Seismic waves can be represented as elastic perturbations propagating within a medium, originated by a transient disequilibrium in the stress field. The properties of seismic waves are ruled by the physics of elastic bodies, and are studied using the formalisms of the elastodynamic theory. The movement of the particles of the ground surface during an earthquake due to the seismic wave propagation can be described by a linear system of three partial differential equations with three unknowns – the three components of the displacement vector, whose parameters depend on spatial variables. Considering the balance of forces, including inertia, body forces and surface forces acting on a cubic element within the continuum, and applying Newton's law, we obtain the system of equations of motion:

$$
\begin{aligned}
\rho \frac{\partial^2 u_x}{\partial t^2} &= \rho \mathrm{X} + \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{yx}}{\partial y} + \frac{\partial \sigma_{zx}}{\partial z} \\
\rho \frac{\partial^2 u_y}{\partial t^2} &= \rho \mathrm{Y} + \frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{zy}}{\partial z} \qquad (1). \\
\rho \frac{\partial^2 u_z}{\partial t^2} &= \rho \mathrm{Z} + \frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{yz}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z}
\end{aligned}
$$

Under the assumption for small deformations and stresses of short duration (conditions mostly satisfied in seismological problems), we can assume that the solid behaves linearly and the constitutive relation linking stresses and deformation becomes the Hooke's law. If the solid is isotropic, we obtain:

$\sigma_{ij} = \lambda e_{kk} d_{ij} + 2\mu e_{ij}$, where λ and μ are the Lame parameters. (2)

Thus we have a linear system of three differential equations with three unknowns: the three components of the displacement vector, whose coefficients depend upon the elastic arameters of the material. It is not possible to find the analytic solution for this system of equations, and therefore it is necessary to add further approximations, chosen according to the adopted resolving method. Two ways can be followed: (1) providing an exact definition of the medium, it is possible to use a direct numerical integration technique for solving the set of differential equations; (2) applying exact analytical techniques to an approximated model of the medium that may have the elastic parameters varying along one or more directions of heterogeneity – it is introduced the analytical solution valid for a flat layered halfspace, that constitutes the base of knowledge for the treatment we will develop for models with lateral discontinuities.

For the case of equations of elastic motion for a halfspace with vertical heterogeneities λ, μ and ρ are functions of z continuous along discrete intervals and become constant below a given depth H. Assuming that α_H ($\alpha= [(\lambda+2\mu)/\rho]^{1/2}$) and β_H ($\beta=(\mu/\rho)^{1/2}$) assume their largest value, α_H and β_H, when z > H; the boundary condition that must be satisfied when solving the equations of motionis the free surface condition at z=0 and the continuity for the displacement and stress components u_x, u_y, u_z,σ_{zx}, ,σ_{zy}, ,σ_{zz},all along the vertical axis, including the point where λ, μ, ρ are discontinuous.

The complete solution can be represented in an integral form. At large distances from the source, compared with the wavelength, the main part of the solution is given by Rayleigh and Love modes [Levshin, 1973; Aki and Richards, 1980]. There are two independent eigenvalues problems for the three components of the vector F= (F_x, F_y, F_z) to be solved: (1) the first one describes the motion in the plane (x, z), i.e. P-SV (Rayleigh) waves and (2) the second on describes the motion in plane (x, y), i.e. SH (Love) waves.

For the case of multimodal method in a layered halfspace, for Love modes the boundary conditions that must be satisfied at any interface are the continuity of the transverse component of displacement, u_y and of the tangential component of stress s_{zy}. Then it is possible to use the Thomson-Haskell method and its modifications [e.g. Schwab and Knopoff, 1972; Florsch et al., 1991] to compute efficiently the multimodal dispersion of surface waves and therefore synthetic seismograms in anelastic media. For the Rayleigh waves the boundary conditions that must be satisfied at any interface are the continuity of the displacement and stress components.

The seismic source is introduced in the medium representing the fault, supposed to be plain, as a discontinuity in the displacement and shear stresses fields, with respect to the fault plane. On the contrary normal stresses are supposed to be continuous across the fault plane. Following the procedure proposed by Kausel and Schwab (1973), we assume that periods and wavelengths which we are interested in are large compared with the rise time and the dimensions of the source. Therefore the source time function, describing the discontinuity of the displacement across the fault, can be approximated with a step function and the source can be seen as a point in space. Details for the decision of the set of the equations of motion are provided by Panza et al. (2001).

Regarding the case of the seismic wave propagation in laterally heterogeneous medium the system (1) is a linear system of three partial differential equations, with parameters that are dependent on the space variables, for which it is not always possible to find an exact analytical solution. Two main classes of methods that can be used to solve the system of equations (1) are distinguished: (a) analytical and (b) numerical methods. The choice of the method to be used depends on the ratio between the wavelength of the seismic signal and the dimensions of the lateral heterogeneities. For the case of investigating the response of a complex sedimentary basin, it can be worth using a numerical approach. Analytical methods should be preferred when dealing with models whose dimensions are several orders of magnitude larger than the representative wavelengths of the computed signal, because of the limitations in the dimensions of the model that affect the numerical techniques. Typically the analytical solution is applied to the regional model characterising the path from the source to the local area of interest, and the numerical solution is applied to model the local site conditions.

All analytical methods that can be used to extend the modal summation technique to laterally heterogeneous media share the idea that the unknown wavefield generated by the lateral heterogeneities is written as a linear combination of base functions representing the normal modes (Love and Rayleigh) of the considered structure, therefore the problem reduces to the computation of the coefficients of this expansion. If we consider a heterogeneous medium made of two layered quarterspaces in welded contact, the traditional method [Alsop, 1966; McGarr and Alsop, 1967] assumes that at a given frequency the set of eigenfunctions is complete for each of the two quarterspaces. If this condition is satisfied, then the unknowns of the problem, i.e. the transmission and reflection coefficients, can be computed assuming the proper continuity conditions at the vertical interface. There are two problems with this approach: 1) at a given frequency the discrete spectrum of the eigenfunctions is not complete and the continuous spectrum should be included, and this requires the cumbersome computation of branch-line integrals; 2) the expansion in series of the base functions can be carried on for a finite number of terms, so that a control over the approximations introduced becomes necessary.

In a modal approach alternative to the original Alsop's method, the coupling coefficients for the modes transmitted and reflected at the vertical interface are computed and the outgoing (inhomogeneous) surface waves are obtained as a superposition of homogeneous and inhomogeneous waves using Snell's law at each section (supposed infinite) of the vertical interface [Alsop et al., 1974]. The main objection to this approach is that the horizontal boundary conditions are no longer satisfied and therefore some diffracted waves, nearby the vertical interface/ are not properly taken into account. Nevertheless it is possible to estimate the amount of approximation introduced, by checking the energy balance between the incoming and the outgoing wavefields. The analytical solution of the problem associated with SH has been elaborated by Romanelli et al. [1996]. For the P-SV problem, the analytical solution is given by Vaccari et al. [1989] for Poissonian media, and extended to non-poissonian media by Romanelli et al. [1997].The basic model treated by these solutions consists of two layered quarterspaces in welded contact, but the formalism can be extended to any laterally heterogeneous structure by using a series of 1-D layered structures in welded contact at the vertical interfaces as shown in figure 3.

For the computation of the Coupling coefficients for Love modes, it is considered a mode of medium I, incident on the vertical interface between medium I and medium II as shown in Figure 3; normal incidence at the vertical interface is considered, but the case of oblique incidence can be treated as well.

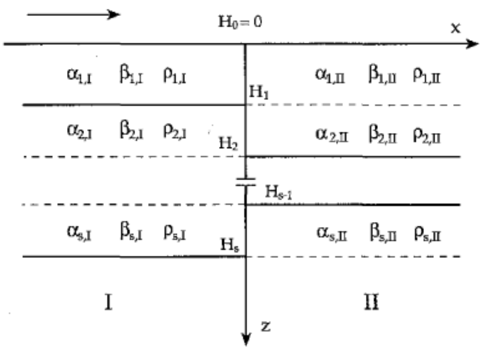


Figure 3. Plane 2D model. The dashed lines show the fictious boundaries, introduced to distinguish the layers of the two quarter spaces.

The stress-displacement vectors associated with transmitted and reflected Modes can be thought as a superposition of propagating modes of medium II and medium I respectively. In each horizontal section the displacement, due to a Love mode, can be written as

$$u_y(x,z,t) = [A_s \cos(kr\beta_s z) + B_s \sin(kr\beta_s z)]e^{i(\omega t - kx)} \qquad (3)$$

$$r_{\beta_s} = \sqrt{\frac{c^2}{\beta_s^2} - 1};\ if\ c > \beta_s\ and\ r_{\beta_s} = -i\sqrt{1 - \frac{c^2}{\beta_s^2}};\ if\ c < \beta_s \qquad (4),$$

where A_s and B_s are the layer constants, c is the phase velocity and β_s is the S-wave velocity in section s.Therefore, in each horizontal section a Love mode can be considered as a superposition of SH-waves incident on the vertical interface with an angle $\theta_s = cos^{-1}\left(\frac{\beta_s}{c}\right)$.

The resulting SH-waves in each section can be homogeneous (θ_S real) or inhomogeneous (θ_S imaginary) according to the values of c, which for a given mode and a given frequency is the same for all the sections, and of the S-wave velocity, which generally varies with varying section. Now the transmission and reflection coefficients can be computed in each horizontal section using Snell's law, which is valid for an infinite surface of contact. The procedure is approximated, since the horizontal boundary conditions are no longer satisfied and not all the diffracted waves are included in the computations.

The transmission coupling coefficient, i.e. the quantity that describes how the amplitude of mode m' in medium II is excited by the incoming mode m of medium I is [Vaccari et al., 1989]:

$$\gamma_T^{(m,m')} = \frac{\langle A_T^{(m)}, A_{II}^{(m)} \rangle}{\langle A_I^{(m)}, A_I^{(m)} \rangle^{1/2} \langle A_{II}^{(m')}, A_{II}^{(m')} \rangle^{1/2}} \qquad (5).$$

If we prefer to consider an incoming mode with unit surface amplitude we need to define a normalization coefficient and the following quantity must be used:

$$\Gamma_T^{(m,m')} = \gamma_T^{(m,m')} \frac{\langle A_I^{(m)}, A_I^{(m)} \rangle^{1/2}}{\langle A_{II}^{(m')}, A_{II}^{(m')} \rangle^{1/2}} = \frac{\langle A_T^{(m)}, A_{II}^{(m)} \rangle}{\langle A_{II}^{(m')}, A_{II}^{(m')} \rangle} \qquad (6).$$

The reflection coupling coefficient can be defined as:

$$\gamma_R^{(m,m')} = \frac{\langle A_R^{(m)}, A_I^{(m)} \rangle}{\langle A_I^{(m)}, A_I^{(m)} \rangle^{\frac{1}{2}} \langle A_{II}^{(m')}, A_{II}^{(m')} \rangle^{\frac{1}{2}}} \qquad (7)$$

while if we consider an incoming mode with unit surface amplitude:

$$\Gamma_R^{(m,m')} = \gamma_R^{(m,m')} \frac{\langle A_{II}^{(m')}, A_{II}^{(m')} \rangle^{1/2}}{\langle A_I^{(m)}, A_I^{(m)} \rangle^{1/2}} = \frac{\langle A_R^{(m)}, A_I^{(m)} \rangle}{\langle A_I^{(m)}, A_I^{(m)} \rangle} \qquad (8).$$

From (8) and considering the orthogonality relations holding at a fixed frequency [e.g. Romanelli et al., 1996], it can be shown that the only non-zero reflection coefficients are those relative to the coupling of homologous modes, i.e. the intra-coupling coefficients.

For Love waves, since in the case of normal incidence there is no conversion of SH-waves into PSVwaves, the vectors stress-deformation are described as follows:

$$A_I = (0, u_{yI}, 0,0, \sigma_{yxI}, 0);$$

$$A_{II} = \left(0, u_{yII}, 0,0, \sigma_{yxII}, 0\right);\ A_T = (0, u_{yT}, 0,0, \sigma_{yxT}, 0) \qquad (9).$$

The analytical solution for the P-SV waves was drawn out by Vaccari et al. [1989] for Poisson medium and it was extended later to non – Poisson medium by Romanelli et al. [1997]. Once the mode coupling coefficients are computed, it becomes possible to compute the displacements due to the Love and Rayleigh modes propagation through the heterogeneous medium [Levshin, 1985]. The displacement in transverse direction related to the movement in the seismic source, associated with the Love mode m and transmitted to mode m’ at distance r from the source is as follows:

$$ {}^{m,m'}U_y(r,z,\omega) = \frac{\exp(-i3\pi/4)}{\sqrt{8\pi}}\left[\frac{\chi_L(h_s,\varphi)S(\omega)}{c_L\sqrt{v_{g,L}I_{1,L}}}\right]_m $$

$$ \left[\frac{\exp\left[-\mathrm{i}\left(k_L\mathrm{d}+k'_L\mathrm{d}\right)-\omega(\mathrm{d}C_{2L}+\mathrm{d}'C'_{2L})\right]}{\sqrt{\mathrm{d}/k_L+\mathrm{d}'/k'_L}}\gamma_{TL}^{(m,m')}\right]_{mm'}\left[\frac{u_z(z,\omega)}{\sqrt{v_{gL}I_{1L}}}\right]_{m'} \qquad (10). $$

Similarly are described the radial and the vertical ground motion components:

$$ {}^{m,m'}U_x(r,z,\omega) = \frac{\exp(-i3\pi/4)}{\sqrt{8\pi}}\left[\frac{\chi_{RL}(h_s,\varphi)S(\omega)}{c_R\sqrt{v_{g,R}I_{1,R}}}\right]_m \qquad (11) $$

$$ \left[\frac{\exp\left[-\mathrm{i}(k_R\mathrm{d}+k'_R\mathrm{d})-\omega(\mathrm{d}C_{2R}+\mathrm{d}'C'_{2R})\right]}{\sqrt{\mathrm{d}/k_R+\mathrm{d}'/k'_R}}\gamma_{TR}^{(m,m')}\right]_{mm'}\left[\frac{u_z(z,\omega)}{\sqrt{v_{gR}I_{1R}}}\right]_{m'} $$

$$ {}^{m,m'}U_z(r,z,\omega) = \exp(-i3\pi/2)\,(\varepsilon_0|_{m'})^{-1}\,{}^{m,m'}U_x(r,z,\omega) \qquad (12). $$

6. DEFINITION OF PRINCIPLE SCENARIOS FOR THE VRANCEA EARTHQUAKES. DEFINITION OF THE PARAMETERS OF THE NUMERICAL MODEL FOR PROGNOSTIC ASSESSMENT OF THE SEISMIC IMPACT OF THE VRANCEA EARTHQUAKES.

6.1. Seismic scenarios

In accordance with the international experience, a reasonable choice of scenario earthquakes should take into account both historical earthquakes record and seismic hazard analysis. The scenario event represents different combinations of parameters, thus the scenario earthquakes can be different in what concerns source location, magnitude and parameters describing the geometry and the kinematics of the seismic source. Usually for an earthquake prone area, scenario earthquakes with different levels of severity are considered: moderate, severe and extreme earthquakes. Widely accepted in international practice in earthquake engineering analysis, including EC8, it is the return period of 475 years. Georgescu and Sandi [2000] observe that the difference between magnitudes with return periods of 200 and of 500 years, respectively, is small and also uncertain, given the uncertainties characterizing the range of the highest magnitudes.

Considering the specific natural conditions, the various categories of elements and systems of risk and the Vrancea earthquake record, for this area, the suitable scenario earthquakes should correspond to return periods ranging from some 50 to 200 years, as far as severe or extreme magnitudes are considered. Suitable alternative Vrancea scenario events can be considered the quakes in magnitude M_w range from 7.2 (severe earthquakes) to 7.8 (extreme earthquakes). Data on the seismic source mechanisms of the intermediate-depth Vrancea earthquakes are published by Dziewonsky et al. [1991] and Radulian et al. [2000]. Information on the uncertainties of these data is available through the Global Centroid Moment Tensor Catalogue via Internet, (http://www.globalcmt.org/CMTsearch.html) and the Romanian Earthquake Catalogue Romplus (www.info.ro/catal/php), first published by Oncescu et al. [1999]. The scenario earthquakes used to define the seismic input are summarized in Table 5.

6.2. Computing model

The structural model used in the computations describes of the seismic wave propagation from the seismic source to the local site. It consists of two horizontally layered half spaces in welded contact, as it is shown in figure 5.

Table 5. Seismic events and scenarios, used for the seismic input modelling

Seismic event	Latitude [°N]	Longitude [°E]	Magnitude Mw	Focal depth km	Strike [°]	Dip [°]	Rake [°]
VR40[1]	45.80	26.70	7.7 - 7.8	150	225	60	80
VR77[2]	45.23	26.17	7.5	83.6	235	62	92
Error				1.1			
VR86[2]	45.76	26.53	7.2	132.7	240	72	97
Error				1.1			
VR901[2]	45.92	26.81	6.9	76.3	236	63	101
Error				0.7/16.0			
VR901[3]	*45.83*	*26.89*		*90.9*			
Error	*2.7km*	*2.2km*		*6.4*			
VR902[2]	45.67	26.00	6.3	87.3	309	69	106
Error				1.3			
VR902[3]	*45.85N*	*26.91E*	*6.4*	*86.9*			
Error	*3.7km*	*3.3km*	*0.1*	*7.2*			
Sce_1[2]	**45.76**	**26.53**	**7.2**	**132.7**	**240**	**72**	**97**
Sce_2[1,4]	**45.80**	**26.70**	**7.8**	**150.0**	**225**	**60**	**80**

* Radulian et al, [2000]; ** Dzievonsky et al, [1991], *** Oncescu et al., [1999], Sce_1** - 30.08.1986, [Dziewonsky et al. 1991], Sce_2*, **** 10.11.1940, [Radulian et al., 2000; Lungu et al.2004].

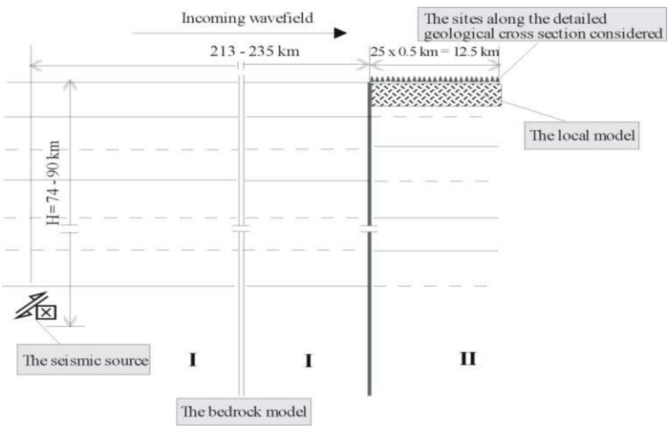
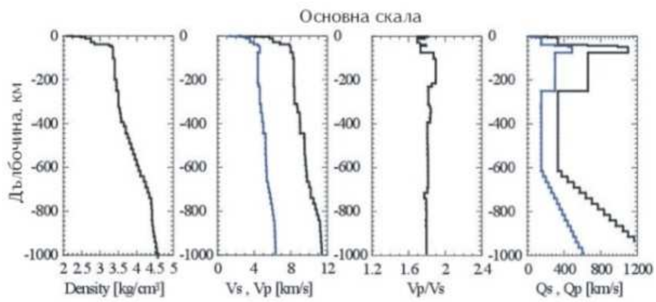


Figure 5. The used model for the performed computations.

The local site model represents the available information for the geological conditions and soils at Russe. The general assessment shows scarce sediments laying on the rock foundation. The target site falls to soil class C according to the EC8 soil classification. The local models, used for the parametric studies as well as for the prognostic seismic loading are shown in Table 6.



Bedrock

thk(km)	rho	Vp(km/s)	Vs(km/s)
0.9000	2.250	2.000000	1.155000
1.1000	2.250	2.500000	1.500000
1.1000	2.450	3.300000	1.830000
3.6000	2.450	3.500000	2.030000
3.6000	2.480	6.500000	2.620000
5.1000	2.480	6.800000	2.800000
5.1000	2.600	5.300000	3.000000
12.2000	2.600	5.500000	3.170000
12.2000	2.700	5.900000	3.450000
30.7000	2.800	6.200000	3.700000
30.7000	2.850	6.700000	3.900000
40.7000	2.850	7.000000	6.030000
40.7000	3.250	7.900000	6.400000

Figure 6. Computing model - Bedrock [Cioflan, 2003].

Table 6. Local structure models according the EC8 soil classification

No	Model	Soil type, EC 8	Velocity model			Note
			V_s^{30} [m/s]	Vp [m/s]	H,[m]	
1	**rs1As, rs5As**	**A**	800	1600	30	**shallow**
2	**rs1Bs, rs5Bs**	**B**	385	770	30	
3	**rs1Cs, rs5Cs**	**C**	325	650	30	
4	**rs1As, rs5As**	**A**	800	1600	60	**intermediate**
5	**rs1Bs, rs5Bs**	**B**	385	770	60	
6	**rs1Cs, rs5Cs**	**C**	325	650	60	
7	**rs1Ad, rs5Ad**	**A**	800	1600	150	**deep**
8	**rs1Bd, rs5Bd**	**B**	385	770	150	
9	**rs1Cd, rs5Cd**	**C**	325	650	150	

7. Generation of Synthetic Seismic Signals for the Site of Russe; Verification and Analysis of the Results.

Theoretical seismic signals following the defined seismic scenarios, shown in Table 5, were computed using the described computing models, given in Table 6. The computations were performed at the University of Trieste, UNITS, and ICTP-Trieste in the framework of several joint research projects, involving UNITS and the Bulgarian Academy of Sciences. The obtained results are accelerograms, velosigrams and seismograms, describing both, the P-SV and SH, wave propagation from the Vrancea sources to the site of Russe.

The following numerical experiments were performed and discussed:

- Computation and verification of the seismic loading at Russe recording station for the Vrancea earthquakes of 30.08.1986 and 30.05.1990;
- Parametric studies of the seismic loading considering the variation of the parameters, describing: (a) the geometry and the kinematics of the seismic source and (b) the geomechanical parameters, describing the local site models;
- Prognostic estimates of the seismic loading and site response for the defined seismic scenarios for strong and extreme earthquakes and different soil types.

7.1. Verification of the method and the obtained results

The verification of the used NDSHA method has been performed providing comparisons of the theoretically computed seismic acceleration time histories and the corresponding recorded time histories. Fourier spectra as well as acceleration response spectra (5%) for the computed and observed signals were also compared. The major part of the comparisons was performed using the results and the records of the VR86 and BR901 data for the frequency band 0 – 1 Hz, e.g. figure 7.

The results of the parametric studies, figure 8-12, show that the transverse component is clearly azimuthally more sensitive to variation of the source, compared to the radial and vertical components, and it practically is not influenced by the dip and the rake angles changes. The radial and the vertical components are quite more sensitive to these source parameters (dip and rake angles). Peak and integral parameters, describing the ground motion damage potential, PGA, PGV, PGD, PGV/PGD, I_A, A_{95}, SA, β, I_D, and T_p are computed for all seismic signals, computed and observed, and the obtained values are given in Tables 7 and 8.

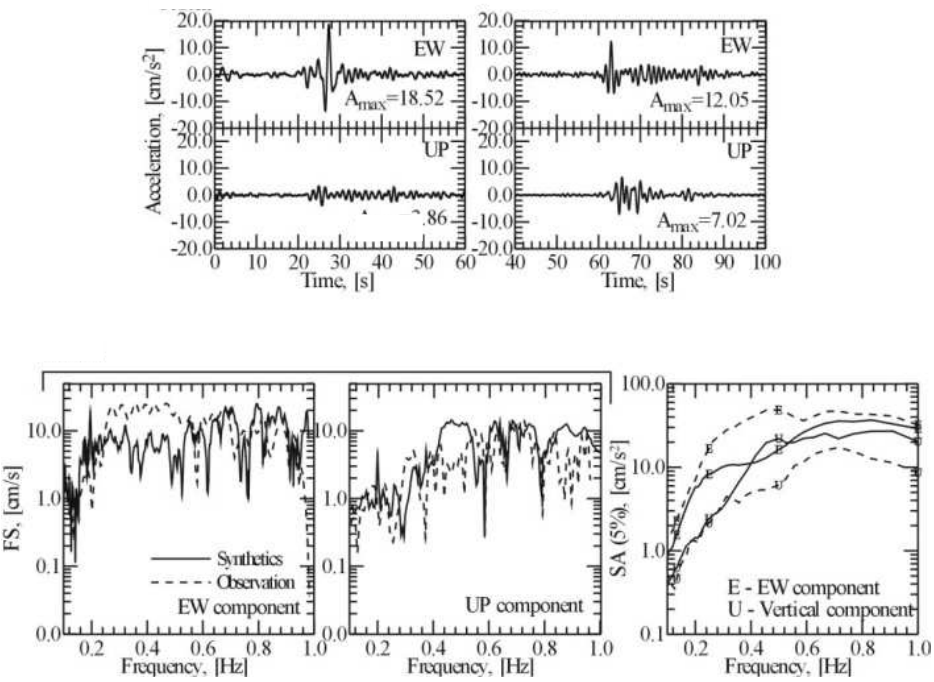


Figure 7. Russe site; Vrancea earthquake 30.08.1986 (VR86). Up: Comparison between the observed (left) and the theoretical (right) accelerograms. Bottom left: Fourier spectra comparison between observed (dashed line) and computed one (solid line). Bottom right: Response spectra comparison between observed (dashed line) and computed one (solid line).

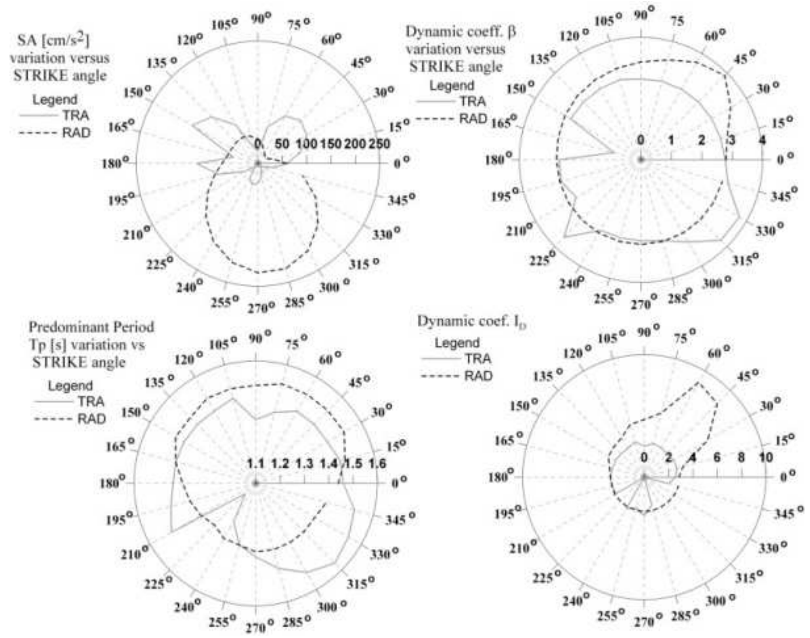


Figure 8. Russe site Русе, Vrancea earthquakes – parametric studies; strike angle variation. Solid line: Transverse (TRA) component; Dashed line: Radial (RAD) component.

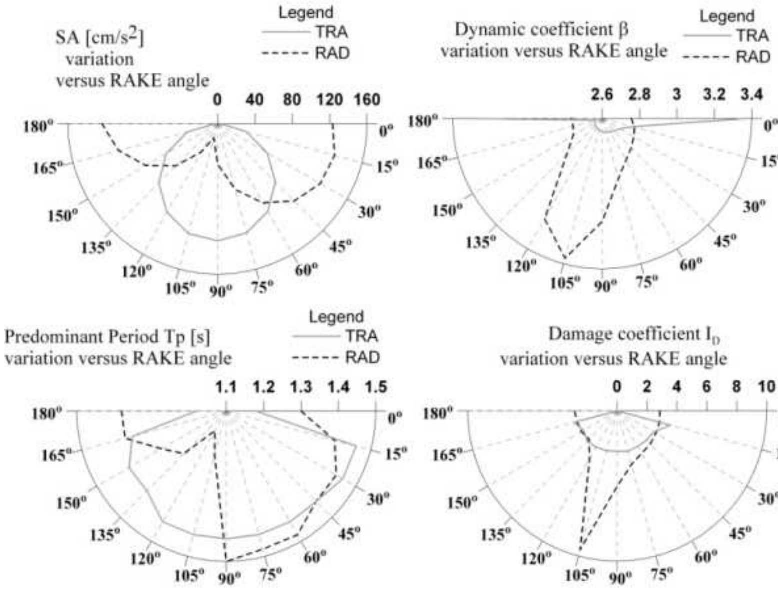


Figure 9. Russe site, Vrancea earthquakes – parametric studies; rake angle variation. Solid line: Transverse (TRA) component; Dashed line: Radial (RAD) component.

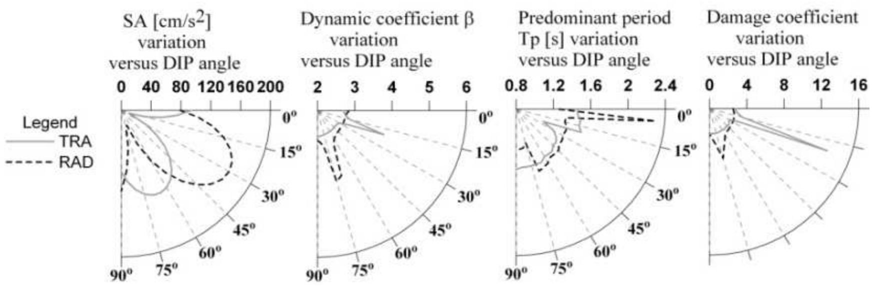


Figure 10. Russe site Pyce, Vrancea earthquakes – parametric studies; dip angle variation. Solid line: Transverse (TRA) component; Dashed line: Radial (RAD) component.

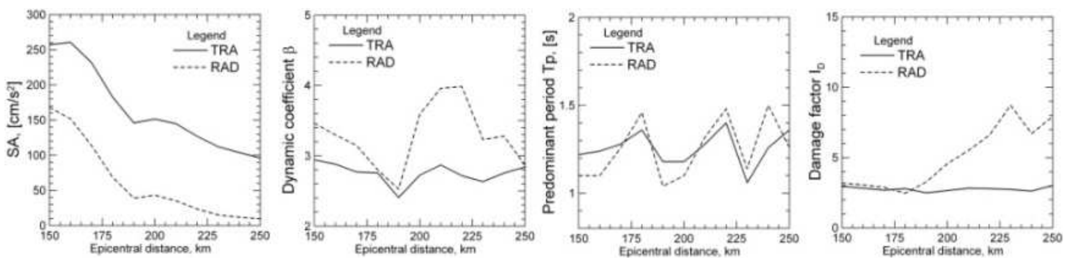


Figure 11. Russe site, Vrancea earthquakes – parametric studies; epicentral distance variation. Solid line: Transverse (TRA) component; Dashed line: Radial (RAD) component.

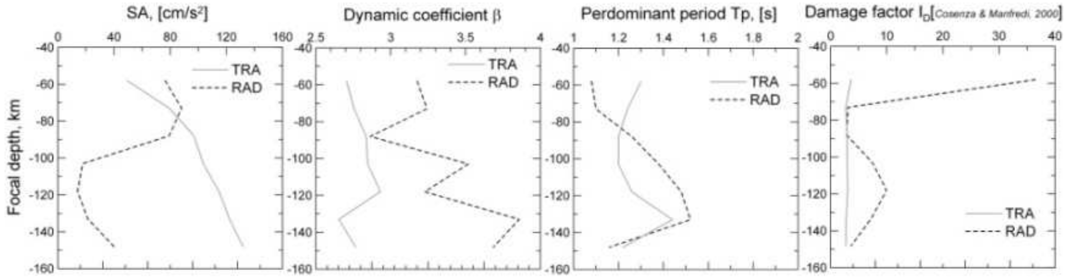


Figure 12. Russe site, Vrancea earthquakes – parametric studies; focal depth variation. Solid line: Transverse (TRA) component; Dashed line: Radial (RAD) component.

All the plots, shown in figures 8-12, indicate clearly the importance of the right estimation of the uncertainties of the parameters, describing the geometry and kinematics of the seismic source and their influence to the seismic loading. Regarding the comparisons of the values of the ground motion parameters of the observed and of the theoretical seismic signals, the best fit is observed for the transverse component, $PGA^{T} = 13.90$ cm/s^2 and $PGA^{OBS} = 14.10$ cm/s^2.

The last group of numerical experiments is the estimation of the soil type on the seismic loading. For this purpose, theoretical accelerograms were computed for all three groups of models – shallow (30m depth of the model), intermediate (60m) and deep (150m) local site models. Each group was related to the EC8 soil classification and soils types A, B and C were considered for these computations. Thus nine local site models were used. The results are shown in figure 13.

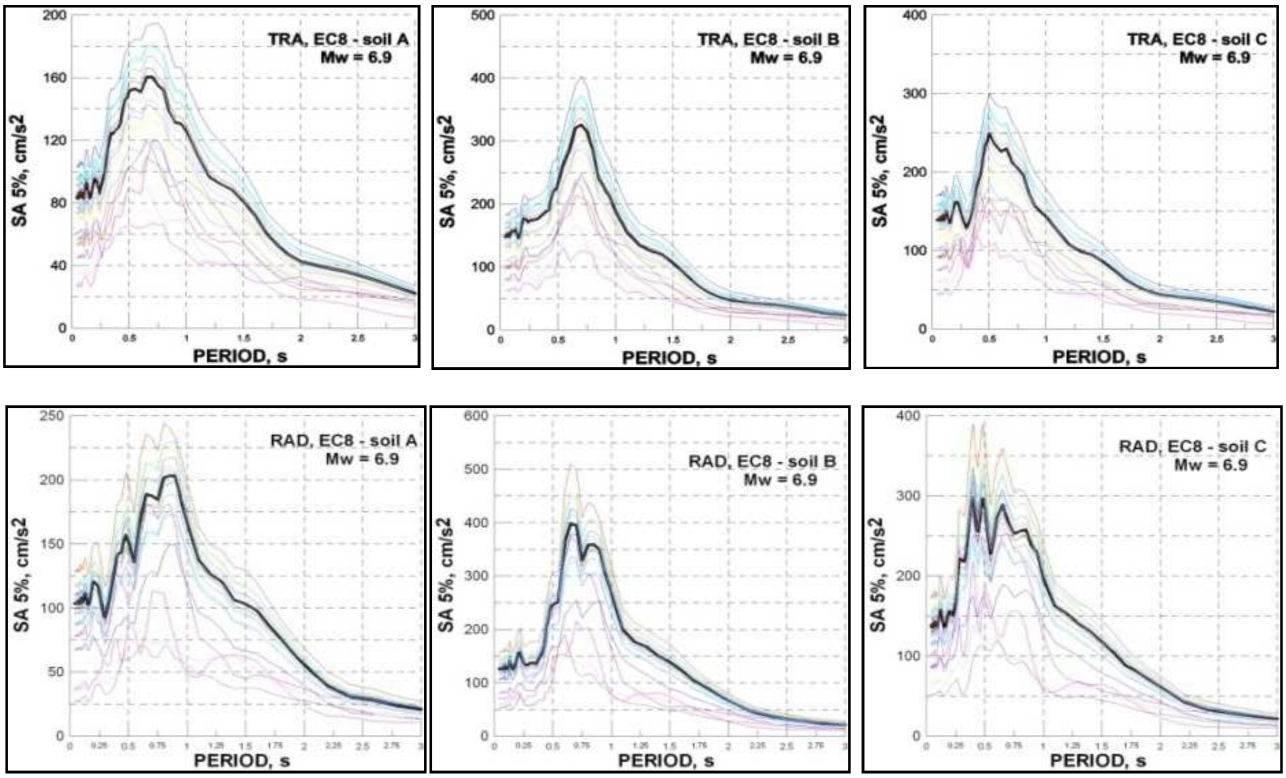


Figure 13. Russe site. Acceleration response spectra (5%) – local site models and seismic source variation. UP: Transverse (TRA) component; Bottom: Radial (RAD) component. Black solid line: the starting model – CMT focal solution and shallow local site model.

Table 7.1. Comparison of the computed values of the response spectral amplitudes and the corresponding observed (OBS) values: SA MAX, [cm/s^2]

SA MAX, [CM/S^2]	Computed Values SA MAX, [CM/S^2]												OBS
VR90	*STRIKE, STR,* [^{0}]			*DEPTH, H,* [KM]			*DIP, DIP,* [^{0}]			*RAKE, RAK,* [^{0}]			STR=41, H=90, DIP=63, RAK=101
	H=90, DIP=63, RAK=101			*STR=41, DIP=63, RAK=101*			*STR=41, H=90, RAK=101*			*STR=41, H=90, DIP=63*			
	31^0	*41^0*	*51^0*	*60*	*70*	*90*	*53^0*	*63^0*	*73^0*	*91^0*	*101^0*	*111^0*	
TRA	35.0	39.7	40.8	34.4	47.3	39.7	43.8	39.7	34.4	36.8	39.7	37.6	38.8
RAD	26.3	29.2	33.6	28.8	31.4	29.2	38.0	29.2	20.0	47.4	29.2	15.5	45.1
VRT	19.1	21.2	24.3	19.6	12.2	21.2	27.5	21.2	14.2	31.6	9.61	21.2	11.4
VR86	*STRIKE, STR,* [^{0}]			*DEPTH, H,* [KM]			*DIP, DIP,* [^{0}]			*RAKE, RAK,* [^{0}]			STR=50, H=133, DIP=72, RAK=97
	H=133, DIP=72, RAK=97			*STR=50, DIP=72, RAK=97*			*STR=50, H=133, RAK=97*			*STR=50, H=133, DIP=97*			
	40^0	*50^0*	*60^0*	*123*	*133*	*143*	*62^0*	*72^0*	*82^0*	*87^0*	*97^0*	*107^0*	
TRA	174.4	167.3	147.6	139.1	167.3	195.7	168.5	167.3	146.9	167.7	167.3	161.8	----
RAD	48.9	53.5	62.1	40.1	53.3	77.6	162.2	53.3	72.4	91.7	53.3	27.2	----
VRT	33.5	37.9	43.2	32.7	37.9	10.8	67.9	37.9	20.5	48.9	37.9	26.0	17.2
EW	27.5	33.7	62.6	30.4	33.7	43.9	131.5	33.7	92.5	63.7	33.7	24.0	48.5

Table 7.2. Comparison of the computed values of the PGA, PGV, PGD, PGV/PGD, I_A, A_{95} (Vrs2dh1* - grey lines) with the corresponding observed values (Rsf010*)**.**

Ground motion component	PGA [cm/s^2]	PGV [cm/s]	PGD [cm]	Arias Intens. cm/s	A95 [g]	PGV/PGA [s]	PGA [cm/s^2]	PGV [cm/s]	PGD [cm]	Arias Intens. cm/s	A95 [g]	PGV/PGA [s]
1	2	3	4	6	7	8						
Frequency content 0 - 1 Hz							**Frequency content 0 - 2 Hz**					
TRA												
Vrs2dh1t	13.90	3.01	0.94	0.228	0.014	0.216	52.80	12.40	3.85	3.763	0.052	0.235
Rsf010t	14.10	2.95	0.80	0.414	0.014	0.209	29.40	4.66	1.04	1.714	0.029	0.159
RAD												
Vrs2dh1r	4.38	1.02	0.25	0.064	0.004	0.233	16.70	2.38	0.45	0.494	0.016	0.142
Rsf010r	9.40	2.50	0.96	0.246	0.009	0.266	18.20	2.40	0.93	0.657	0.018	0.132
VER												
Vrs2dh1v	1.90	0.45	0.19	0.021	0.002	0.237	6.30	0.94	0.19	0.080	0.006	0.149
Rsf010v	3.90	0.95	0.48	0.060	0.004	0.244	7.80	0.95	0.48	0.150	0.004	0.121

7.2. Prognostic estimations of the seismic loading for Bulgaria for strong and extreme Vrancea Earthquake scenarios

The prognostic values of the dynamic coefficients, based on the computed acceleration response spectra (5%) for strong and extreme Vrancea earthquake scenario, considering different soil types and different epicentral distances, corresponding to different sites of interest in Bulgaria are shown in figures 14 (strong seismic event) and figure 15 (extreme seismic event). The plots of the dynamic coefficient, proposed in the National Application of the Eurocode 8 are shown in the same figures.

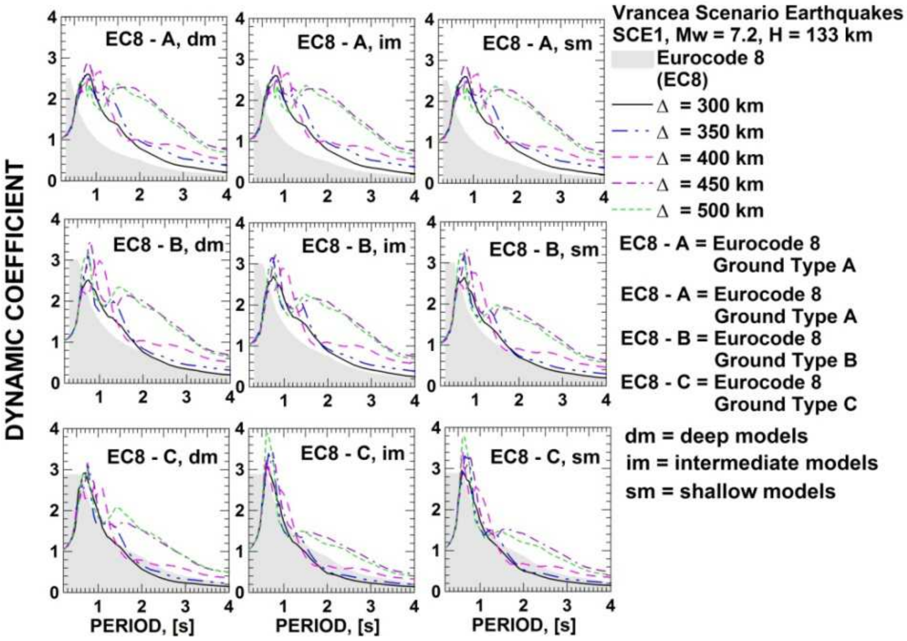


Figure 14. Scenario of strong Vrancea earthquake - dynamic coefficients. Comparison of the computed values with the values, prescribed in the legislation, EC8.

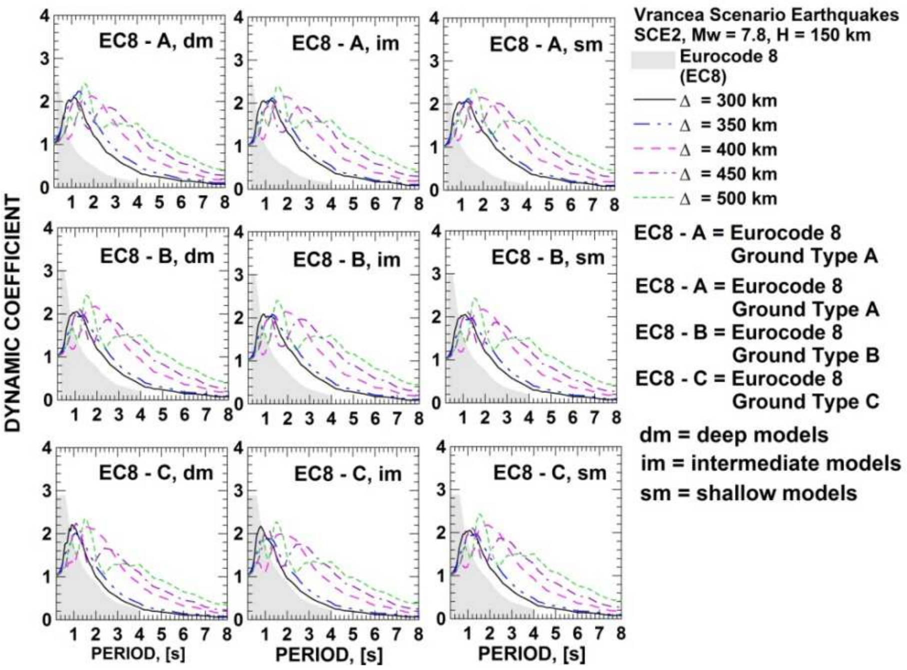


Figure 15. Scenario of extreme Vrancea earthquake - dynamic coefficients. Comparison of the computed values with the values, prescribed in the legislation, EC8.

8. Conclusions and Future Work

8.1. Major conclusions

The modeling of the strong intermediate-focus Vrancea earthquakes has been performed making use of analytical neo-deterministic procedure. The choice of the procedure is based on the performed comparative analysis of the contemporary advanced methods for modeling of the seismic loading. This method uses the available information and data about the seismicity, the seismic source and geology of the region and the local site of interest, without requests for any additional geological survey. The main advantage of the proposed neo-deterministic procedure is the simultaneous treatment of the contribution of the seismic source and seismic wave propagation media to the strong motion at the target site/region, as required by basic physical principles.

The performed analyses have shown that changes in the geometry and the kinematics of the seismic source in reasonable tolerance influence the amplitude of the seismic signal and do not practically change the spectrum of the seismic loading. The uncertainties of the computations of the focal depth are the most important for the waveform compared to the other parameters, describing the geometry and the kinematics of the seismic source.

The application of the neo-deterministic procedure gives the possibility for assessment of the site response. The irregular amplification of the seismic signal in the soil, considering even the used, strongly simplified, model confirms the complex character of the site response, which reflects the process of seismic wave propagation (transition, refraction and reflection) from the seismic source to the local site of interest.

Two major seismic scenarios for prognostic assessment of the seismic loading in Bulgaria due to the strong intermediate focus Vrancea earthquakes have been defined: strong event M_w = 7.2 and very strong (destructive) event M_w = 7.8. Following these two scenarios theoretical accelerograms were computed, considering nine different local site models, corresponding to soils of Type A, B and C according the EC8 soil classification. The considered sites of interest, used for the computations cover epicentral distances range of 200 to 400 km. The obtained results have shown that the used procedure is capable to provide results that are compatible with the requirement of the legislation with regard to the alternative representation of the seismic loading, using time histories. Therefore the obtained results might be used for earthquake engineering purposes. These results have also shown that we have to take particular care for the definition of the seismic loading for long period structures, when they might be exposed strong Vrancea earthquakes.

The performed data analysis and the obtained results of the performed parametric analyses were considered by the motivation of the necessity to define particular design response spectra for the Vrancea earthquakes. Thus a new response spectrum, Type 3, has been proposed to be included in the National Application of the Eurocode 8 in Bulgaria.

8.2. Further studies and use of the obtained results.

The theoretically obtained seismic signals, accelerograms, velosigrams and seismograms, describing the ground motion during given earthquake might be used directly for earthquake engineering purposes – dynamic analyses of structures, retrofitting, damage index assessments, urban planning, earthquake preparedness.

The analysis of the theoretical velosigrams allows us to compute the peak ground velocities, PGV, that might be used for estimation of the ground deformations and thus it is possible to perform different damage estimations [Trifunac & Todorovska, 1997]. The possibility for assessment of the superficial deformations is particularly important for long (extended in plan) structures.

The neo-deterministic procedure for seismic loading definition that was used in this study might be directly applied for seismic microzonation, associating areas with given geological conditions with the corresponding ground motion parameters as acceleration response spectra amplitudes, S_a, or spectral displacement, S_d, or demand diagram S_a-S_d.

Further organization of the obtained results (accelerograms, velosigrams and seismograms) in an automatic database would provide conditions for elaboration advanced solutions for automatic estimation of different ground motion parameters, relevant to the seismic risk assessment.

MAJOR SCIENTIFIC AND SCIENTIFIC APPLICATION CONTRIBUTIONS

I. The dissertation provides results and analyses of the first application of the analytical neo-deterministic procedure for modeling and prognostic assessment of the seismic loading at sites, located at large epicentral distances (~200 km) due to earthquakes with focal depths ~120-130 km. It is the first application of this contemporary method for modelling the seismic wave propagation in real heterogeneous medium for Bulgarian case study.

II. It is shown that the geometry and kinematics of the seismic source influence the amplitudes of the seismic signal of the strong intermediate-focus Vrancea earthquakes, but do not change the frequency content of the signal.

III. The frequency content of the wave forms of the seismic loading due to the strong intermediate-focus Vrancea earthquakes is influenced in similar degree by both, local geological characteristics of the site and the earthquake focal depth.

IV. Two principle seismic scenarios for prognostic assessment of the seismic loading in Bulgaria due to the strong intermediate-focus Vrancea earthquakes have been formulated:
(1) strong earthquake, magnitude $M_w = 7.2$;
(2) very strong, damaging, earthquake, magnitude $M_w = 7.8$.

V. All the performed analyses and the obtained results were among the motivations that have been used for the motivation of the necessity of definition of particular spectrum in the National Application of the Eurocode 8, relevant to the Vrancea earthquakes.

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