# STRONG INTERMEDIATE-DEPTH VRANCEA EARTHQUAKES: DAMAGE CAPACITY IN BULGARIA

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**ABSTRACT :**

The sustainable development of the society depends not only on a reasonable policy for economical growth but also on the reasonable management of natural risks. The regional earthquake danger due to the Vrancea intermediate-depth earthquakes dominates the hazard of NE Bulgaria. These quakes have particularly long-period and far-reaching effects, causing damages at large epicentral distances. Vrancea events energy attenuates considerably less rapidly than that of the wave field radiated by the seismically active zones in Bulgaria. The available strong motion records at Russe, NE Bulgaria, due to both Vrancea events - August 30, 1986 and May 30, 1990 show higher seismic response spectra amplitudes for periods up to 0.6 s for the horizontal components, compared to the values given in the Bulgarian Code and Eurocode 8. A neo-deterministic analytical procedure which models the wavefield generated by a realistic earthquake source, as it propagates through a laterally varying anelastic medium, is applied to obtain the seismic loading at Russe. After proper validation, using the few available data and parametric analyses, from the synthesized seismic signals damage capacity of selected scenario Vrancea quakes is estimated and compared with available capacity curves for some reinforced concrete and masonry structures, representative of the Balkan Region. The performed modelling has shown that the earthquake focal mechanisms control the seismic loading much more than the local geology, and that the site response should be analyzed by considering the whole thickness of sediments until the bedrock, and not only the topmost 30 m.

**KEYWORDS:** seismic input, intermediate-depth earthquake, neo-deterministic ground motion modelling procedure, scenario earthquake, earthquake capacity diagram.

## 1. THE VRANCEA EARTHQUAKE HAZARD

The Vrancea subduction seismogenic zone is a peculiar intermediate-depth source that, in case of large magnitude earthquake, strongly affects a significant part of the Bulgarian territory including major cities in NE Bulgaria, among which the biggest Bulgarian port on the Danube - the town of Russe. 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 epicenters of Vrancea events recorded in the period from 1900 to 1980 occupy an ellipse-like area, with some irregular extensions towards NE, SW and SE. The isoseismal areas are strongly stretched towards NE-EW (N45$^o$E - N225$^o$E) for some earthquakes (1940, 1977), but there are also other historical data that show isoseismal ellipses slightly "turned" anti-clockwise (1802) or even oriented perpendicular to the usual direction. The focal depth of the strong events is about 100 km, the increase of magnitude appears to be positively correlated with the increase of depth [Georgescu and Sandi, 2000 and references therein].

The Vrancea intermediate depth quakes with magnitude M≥7.0 are felt at very large distances, up to 1000 km and NE Bulgaria is affected by intensities I≥VI (MSK). Some times local culminations of intensities can be recorded at epicentral distances of 200 - 300 km, like the above VII intensity documented, in 1977, at Russe. Most of the damage due to strong Vrancea earthquakes, so far, refers to the built stock constructed before the 1980 (Low Code period when the earthquake resistant design deals with a unique arbitrary base shear seismic coefficient), even before 1970 (Pre-Code period, when no seismic regulation were available). This fact, the lack of enough instrumental strong motion records and the peculiarity of the intermediate-depth Vrancea seismic source call our attention to the necessity of providing, by modelling, reliable seismic input that might be used for the purpose of retrofitting and urban planning.

## 2. THE NEO-DETERMINISTIC GROUND MOTION MODELLING PROCEDURE: APPLICATION FOR THE CASE-STUDY OF RUSSE, NE BULGARIA

A neo-deterministic analytical procedure has been applied to obtain the seismic input at Russe [Panza et al., 2001]. The major advantage of the applied neo-deterministic procedure is the simultaneous treatment of the contribution of the seismic source and of the seismic wave propagation media to the strong motion at the target site/region, as required by basic physical principles. Generally, the computation model, describing the seismic wave propagation path from the seismic source to the target site consists of two structural models, bedrock, representing the travel path from the source to the site, and local model, representing the local engineering geological features of the site of interest. To model the seismic input at Russe the analytical neo-deterministic approach based on mode coupling technique, is used [Romanelli et al., 1996; 1997].

### *2.1. Input data*

*2.1.1 Seismic wave propagation path*

The structural model used in the computations consists of two horizontally layered half spaces in welded contact. The bedrock structure contains the source and the path from the Vrancea seismic sources to the target sites. The profile Vrancea-Russe passes through the Carpathians and the Moesian Platform, where Pliocene and significant Quaternary deposits are present. Details on the computation model and on the geological information used are published by Paskaleva et al. [2001]. In this study the target site of Russe is represented by three generalized local geological models corresponding to the soil classes A, B and C according to the Eurocode 8 (EC8) ground type classification. A summary of the local geological velocity models, constructed following the EC8 soil classification and used in this study, is given in Table 1.

*2.1.2 Scenario earthquakes*

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 (Gutenberg-Richter) range from 7.2 (severe earthquakes) to 7.6 (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 2.

Table 1. Local site velocity models

| No | Ground Type according EC8 | Density, [kg/m$^3$] | Vs [m/s] | Vp [m/s] | Layer thickness [m] | Local model depth [m] | $V_s^{30}$ [m/s] | models' abbreviation |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| | shallow | | | | | | | |
| 1 | A | 1900 | 800 | 1200 | 30 | 30 | 800 | rs1As/ rs3As |
| 2 | B | 1900 | 385 | 800 | 30 | | 385 | rs1Bs /rs3Bs |
| 3 | C | 1900 | 150 | 360 | 5 | | | rs1Cs /rs3Cs |
| | | | 325 | 670 | 15 | | | |
| | | | 800 | 1750 | 10 | | 325 | |
| | intermediate | depth | | | | | | |
| 4 | A | 1900 | 800 | 1200 | 60 | 60 | 800 | rs1Ai/ rs3Ai |
| 5 | B | 1900 | 385 | 800 | 30 | | 385 | rs1Bi/ rs3Bi |
| | | | 800 | 1750 | 30 | | | |
| 6 | C | 1900 | 225 | 400 | 10 | | | rs1Ci /rs3Ci |
| | | | 400 | 810 | 20 | | | |
| | | | 410 | 830 | 15 | | | |
| | | | 800 | 1600 | 15 | | 325 | |
| | deep | | | | | | | |
| 7 | A | 1900 | 800 | 1200 | 150 | 150 | 800 | rs1Ad/ rs3Ad |
| 8 | B | 1900 | 385 | 800 | 30 | | | rs1Bd/ rs3Bd |
| | | | 800 | 1750 | 120 | | 385 | |
| 9 | C | 1900 | 225 | 400 | 10 | | | rs1Cd /rs3Cd |
| | | | 400 | 810 | 20 | | | |
| | | | 410 | 830 | 15 | | | |
| | | | 800 | 1600 | 95 | | 325 | |

Table 2. Scenario Vrancea earthquakes

| Quake * abbr | Lat. (°N) | Long. (°E) | Magnitude Mw | Focal depth, km | Strike angle,° | Dip angle,° | Rake angle, ° |
|---|---|---|---|---|---|---|---|
| VR901 | 45.92 | 26.81 | 6.9 | 74.3 +/- 6 km | 236 | 63 | 101 |
| Sce_1 | 45.76 | 26.53 | 7.2 | 132.7 | 240 | 72 | 97 |
| Sce_2 | 45.80 | 26.7 | 7.8 | 150 | 225 | 60 | 80 |

* VR901 corresponds to the Vrancea 1990 earthquake (May 30) as reported by Dzievonsky et al. [1991]; Sce_1 seismic source description corresponds to the 1986 Vrancea quake (August 30) Dzievonsky et al. [1991] and Sce_2 corresponds to the Vrancea 1940, Nov. 10, earthquake [Radulian et al., 2000 and references therein].

### *2.2. Simulation tests and results verification*

Following the models defined in Table 1 and the earthquake scenarios given in Table 2, three component accelerograms and the corresponding generalized earthquake loading horizontal vector (HSL) are computed, considering frequency contents 0-1 Hz and 0-3Hz. The available instrumental records at Russe, due to the Vrancea earthquake of May 30, 1990, have been used for validation of the ground motion modelling technique applied to define the seismic input, considering ground type C (Table 1) for the target site. Peak ground acceleration (PGA), absolute energy input ($E_I$), computed following Decanini and Mollaioli [1998] and capacity diagram (5% damping response spectral displacements SD versus 5% damping response spectral accelerations SA) are computed for both synthetic and recorded signals. The PGA comparisons for both components, transverse (TRA) and radial (RAD) are shown Figures 1 and 2, for frequency content of the seismic signals 0 - 1 Hz and 0 - 3 Hz, respectively. Considering the available information on the focal depth of the seismic source and the possible uncertainties in the seismic source location, three focal depths are taken into account - 74 km, 80 km and 90 km. Time scales for both synthetic and observed signals differ, since the recorded accelerograms are obtained by SMA - 1 analogue instruments, which are not equipped by any time synchronizing device, while the synthetic seismogram represents the first 200 s of ground acceleration time history. Figure 1 shows that the best fit synthetics-observations for the transverse component, TRA, (frequency content 0 - 1 Hz) corresponds to the focal depth H = 80 km, while for the radial one, RAD, the focal depth H = 74 km gives a better fit synthetics-observation. This difference in depth is immaterial for engineering purposes.

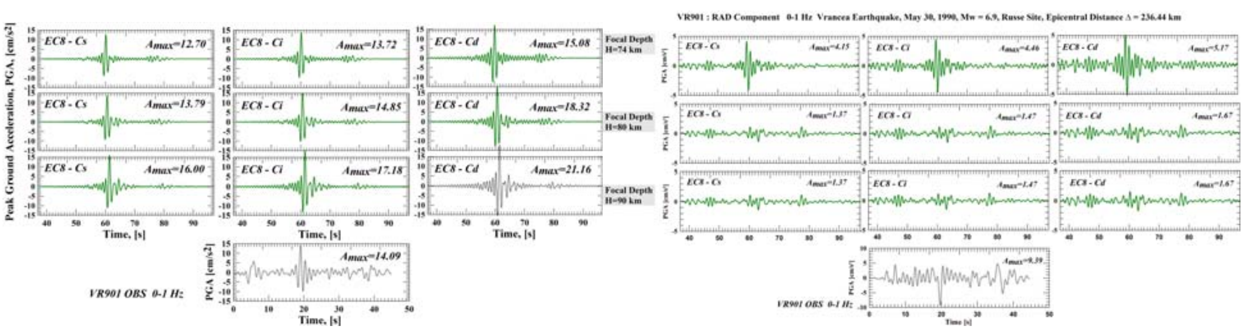


Figure 1 Vrancea earthquake, May 30, 1990, Mw = 6.9, Russe site (epicentral distance Δ = 236.45km). Left: Transversal component, Right: Radial Component. Frequency content 0 - 1Hz. First row corresponds to focal depth H = 74 km, second row: H = 80 km, third row: H = 90 km. Three local site models are considered: shallow, Cs, intermediate, Ci, and deep, Cd.

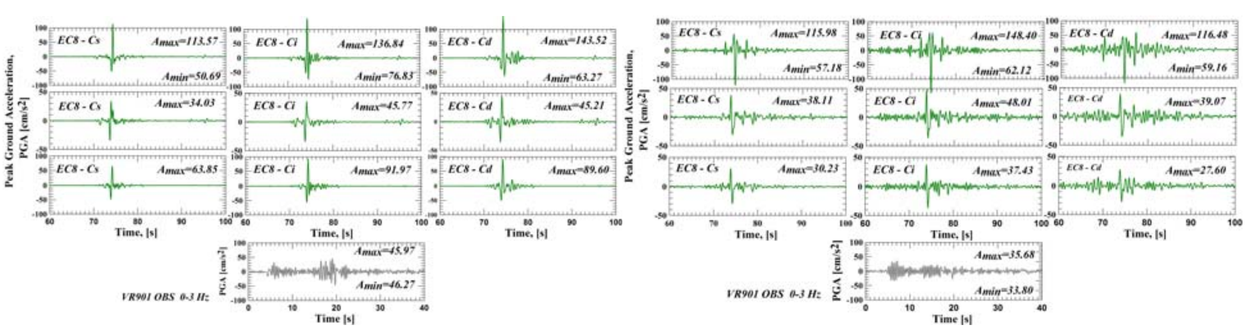


Figure 2 Vrancea earthquake, May 30, 1990, Mw = 6.9, focal depth = 80 km, Russe site (epicentral distance Δ = 236.45km). Left: Transversal component, Right: Radial Component. Frequency content 0 - 3Hz. First row corresponds to focal depth H = 74 km, second row: H = 80 km, third row: H = 90 km. Three local site models considered: shallow, Cs, intermediate, Ci, and deep, Cd.

The comparison of the seismic acceleration time histories, computed for frequency content 0 - 3 Hz, given in Figure 2, provides the best signal shape and PGA fits synthetics-observation for the focal depth H = 80 km. The performed parametric analyses, considering the chosen bedrock structure, indicate the significant contribution of the Vrancea seismic source, particularly its focal depth and dip angle, to the seismic input at Russe site [Kouteva et al., 2004; Kouteva, 2008]. The RAD PGA decreases with decreasing focal depths, from H = 65 to 75 km, and then it remains almost constant for H > 80 km. Regarding dip and rake angle, RAD PGA increases gradually with rake angle, and dip angle > 60$^o$ - these values increase about twice for dip = 60 - 70$^o$. The TRA PGA decreases gradually with increasing rake and dip angle. Regarding the focal depth, the TRA PGA decreases for 75 <H< 80 km and then starts to increase for H > 80 km.

The comparison of $E_I$, the absolute energy input [Decanini and Mollaioli, 1998], with frequency content 0 - 3 Hz is shown in Figure 3. The results shown in this figure represent three local models, corresponding to EC8 ground type C, which differs in the thickness of the superficial ground layer, and focal depths H equal to 74, 80 and 90 km. It is obvious that the synthetics overestimate the observation for all models considered. The visible shift of the maximum of the $E_I$ maximum for both components is most probably due to the not sufficiently detailed uppermost geological model. Generally the $E_I$ trend for both TRA and RAD components is most properly kept considering the intermediate local model rs3Ci and H = 74 km. Looking at the $E_I$ amplitudes for period T > 0.7 s a better fit is obtained for H = 80 km and the shallow (intermediate) model for the TRA and H = 90 for the RAD component, respectively.

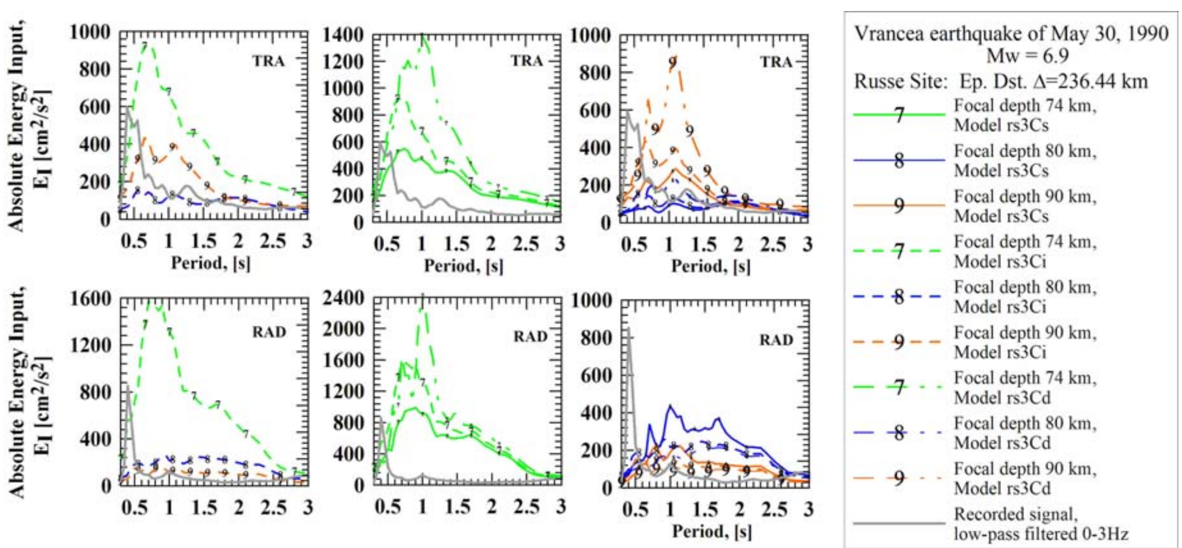


Figure 3 Vrancea earthquake, May 30, 1990, Mw = 6.9, focal depth = 80 km, Absolute Energy Input at Russe site (epicentral distance Δ = 236.45km). TRA: Transversal component, RAD: Radial Component.

The capacity diagram of the computed and the corresponding recorded signals (0-3Hz, model rs3Cs, rs3Ci and rs3Cd) are compared in Figure 4. The capacity is given in terms of response spectral displacements, versus response spectral accelerations, SD-SA computed for 5% damping. Both horizontal components and the horizontal vector of the earthquake loading (HSL) are shown for the local site models rs3Cs, rs3Ci and rs3CD and focal depths H = 74, 80 and 90 km. In the same figure different capacity curves corresponding to some reasonable perturbation in the values of the focal mechanism parameters are shown. The strike angle seems to have a significant influence on the horizontal vector of the seismic loading and its capacity curve (pink lines and crosses in Fig. 4). Figure 4 shows that synthetics largely envelop the observations for all cases considered, thus supply conservative estimates. A look at the qualitative agreement of the capacity spectra indicates the rs3Ci model as the most appropriate one for all focal depths considered.

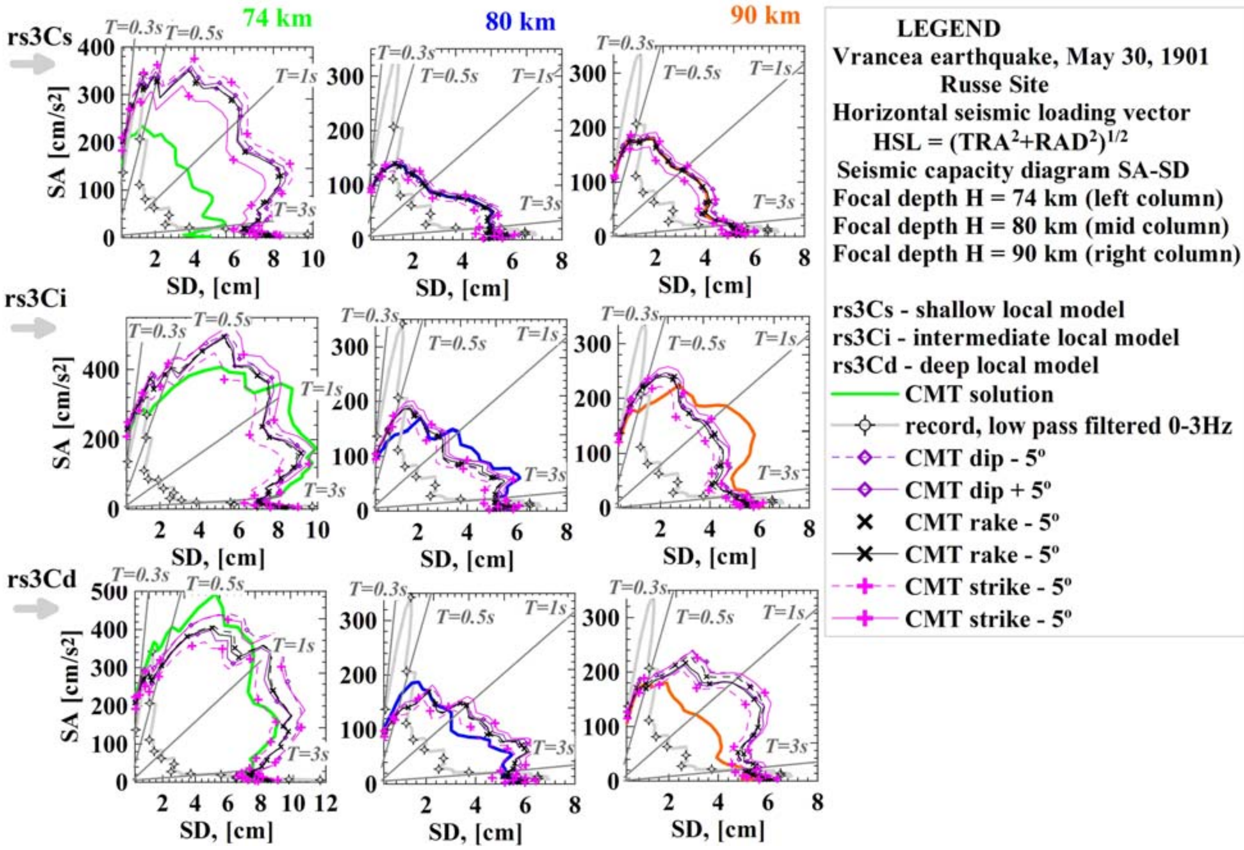


Figure 4 Vrancea earthquake, May 30, 1990, Mw = 6.9, Earthquake Capacity at Russe site (epicentral distance Δ = 236.45km). TRA: Transversal component, RAD: Radial Component, HSL - horizontal vector of the earthquake loading. The tick lines show the synthetic signal corresponding to the CMT data, the grey line (circles) represents the observation.

### *2.3. Estimates of the damage capacity of the selected scenario events*

Finally, the capacity spectra for the two chosen scenario earthquakes have been computed, considering all local ground models following EC8 (Table 1). The results of these computations are shown in Figure 5 - Sce_1, strong event and Sce_2, extreme event. Both, TRA component (black ticker lines) and the horizontal vector of the earthquake loading HSL (thinner grey lines) are shown. The scenario earthquake capacity diagram overlaps the capacity curves of some mid-rise reinforced structures, representative for the Balkan region for different periods of the developments of the seismic regulations for design and construction [Kappos et al., 2002; Milotinovic and Trendafiloski, 2003]. A comparison between Sce_1 and Sce_2 shows that the residential built stock is most vulnerable to the severe (more frequent) events. Figure 5 calls our attention on the fact that the stronger and deeper event Sce_2 (Mw = 7.8, H = 150 km) keeps the levels of the response spectral acceleration for 5% damping, but creates twice larger response spectral displacements, compared to Sce_1 (Mw = 7.2, H = 133 km). In fact, the Sce_2 results are in agreement with the recently published maps of seismic hazard numerically modelled peak amplitudes of the horizontal ground motion, displacement, velocity and design ground acceleration for some European countries [Panza & Vaccari, 2000]. To construct these maps a circle with 350 km radius centered on Vrancea epicenter cell has been considered, hypocentral depths of 90 km have been associated to events with magnitude 7.4 and depths of 150 km for larger quakes. The scenarios, considered to create these maps, have shown maximum displacement at Russe of 15 - 30 cm, maximum velocity of 30 - 60 cm/s and design ground acceleration – 0.3 - 0.6g. It is obvious the change of the frequency content of the capacity spectra and the low-frequency (long-period) contribution to the seismic input for Sce_2. Figure 5 also indicates that Sce_1 is more sensitive to the local model changes, compared to Sce_2. For ground types A and B the use of shallow and intermediate local models does not lead to visibly different results, for Sce_2 these models can be considered identical. Figure 5 clearly illustrates more significant influence of the seismic source on the seismic input compared to the local geology at the considered site.

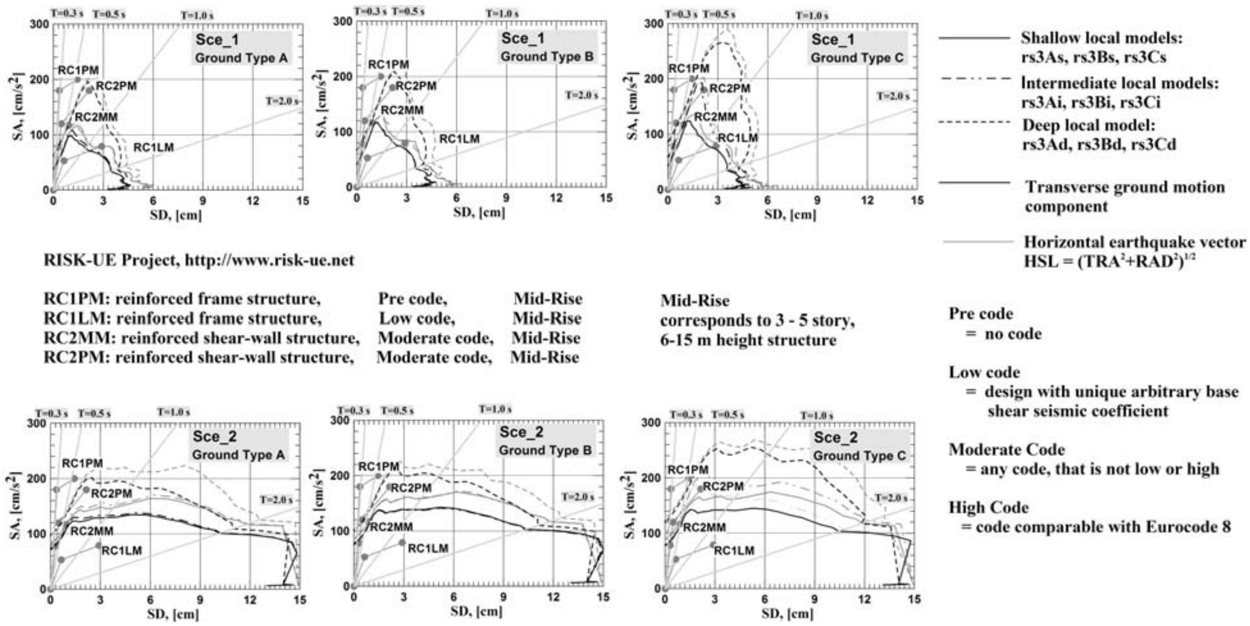


Figure 5 Theoretical estimates of the capacity diagram of Vrancea Scenario earthquakes: Sce_1: strong event, Mw=7.2; Sce_2: extreme event, Mw=7.8. Hypocentres' location and seismic sources - according to Table 2.

## 3. DISCUSSION

Urban areas located at rather large distances (> 200 km) from earthquake sources may be prone to severe earthquake hazard as well as the near field sites. For areas, exposed to high earthquake hazard, where very limited or no recordings are available (e.g. Bulgaria and main Bulgarian cities) synthetic time series can be used to estimate the expected ground motion, thus leading to a pre-disaster microzonation without having to wait for an earthquake to occur. The use of synthetic computations is also necessary to overcome the fact that the local site response can be strongly dependent upon the properties of the seismic source generating the seismic input.

The applied neo-deterministic procedure provides realistic seismic input, which could be directly used in (a) earthquake engineering practice, (b) urban planning, (c) land using, (d) design of new constructions, (e) estimates of the earthquake resistant capacity of the existing built stock and (f) metropolitan seismic microzonation. This scenario-based methodology is strictly based on observable facts and data and it is complemented by physical modelling techniques, which can be submitted to a formalized validation process. By means of sensitivity analysis, knowledge gaps related to lack of data can be dealt with easily, due to the limited amount of scenarios to be investigated.

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