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DESIGN DISPLACEMENT RESPONSE SPECTRA FOR SOUTHERN AND EASTERN ROMANIA

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Abstract

This study is focused on the assessment of displacement response spectra for the southern and eastern part of Romania which are under the influence of the Vrancea subcrustal seismic source. The evaluation of the displacement response spectra is performed using two approaches. In the first approach, the displacement response spectra are computed from stochastic finite-fault simulations obtained for 32 sites situated in the southern and eastern part of Romania and which are under the dominant influence of the intermediate-depth Vrancea seismic source. The soil conditions for each site are evaluated using the horizontal-to-vertical spectral ratio technique, while the earthquake epicenters for the simulated earthquakes are proposed using the seismicity of the XXth century. In the second approach, the displacement response spectra are obtained through probabilistic seismic hazard assessment using the results from hazard models published recently in the literature. Finally, the results are compared with the provisions from the current Romanian seismic design code P100-1/2013. The study highlights two main aspects: (i) the need for more studies related to the evaluation of soil conditions in Romania and (ii) the need to supplement the existing database of strong ground motions recorded during Vrancea intermediate-depth earthquakes with simulated ground motions in order to gain more information regarding the influence of the earthquake magnitude and local site conditions on the spectral displacements.

Keywords: Vrancea seismic source; ground motions; stochastic simulations; seismic hazard; soil conditions.

1. Introduction

This study is a continuation and an extension of a recent study of Pavel and Vacareanu [1]. The focus of study [1] is related to the assessment of the soil conditions for 32 sites in Romania and to the evaluation of the impact of soil conditions on the spectral accelerations and eventually on the seismic hazard levels. This study uses some of the information already acquired and extends it to the evaluation of spectral displacements. The current Romanian seismic design code P100-1/2013 [2] is characterized by a mean return period (MRP) of the seismic action of 225 years (20% exceedance probability in 50 years), which represents an intermediary step before adopting a mean return period of 475 years in a future version of the code. The design code defines the seismic action based on a single parameter of the ground motion, namely the peak ground acceleration. The seismic zonation map of the Romanian seismic design code P100-1/2013 (2013) is divided into seven regions of equal PGA levels in the range 0.10–0.40 g with a constant acceleration step of 0.05 g. The design elastic response spectra in the Romanian seismic code provide spectral ordinates up to T = 4.0 s, are characterized by three values of the control period T_C of 0.7, 1.0 and 1.6 s, a T_B control period dependent on the value of T_C (T_C = 0.2T_B) and two values of control period T_D of 2.0 and 3.0 s. In recent years, especially in the Bucharest region, several RC and steel structures with heights of over 100 m have been built. The fundamental period of these structures is close to the limit of 4.0 s given by the code response spectrum and as such there is a stringent need to evaluate in a correct manner the spectral displacements imposed to these structures. The evaluation of the spectral displacements is performed in this paper by simulating ground motions for intermediate-depth Vrancea earthquakes and by evaluating the uniform hazard spectra obtained through probabilistic seismic hazard assessment (PSHA).

The Vrancea intermediate-depth seismic source represents an area of subcrustal seismicity situated at the bend of the Carpathian Mountains in Romania. The majority of the earthquakes which originate in this seismic source are characterized by reverse faulting mechanisms and the focal depths are mainly concentrated in the range 60 – 170 km [3, 4]. In addition, four earthquakes with magnitudes $M_W \geq 7.1$ occurred in the past century alone in 1908, 1940, 1977 and 1986 (nine events in the past two centuries). A total of 59 earthquakes with $M_W \geq 6.0$ were produced in the past 200 years by this extremely active seismic source. The seismic moment release of this seismic source is of the same order of magnitude as that of southern California [5], and the seismic moment release of the Vrancea intermediate-depth seismic source in the XXth century is three times larger than the seismic moment released through all the earthquakes in Italy in the same century [6]. In addition, the Vrancea earthquake of November 1940 (M_W = 7.7) can be considered as the largest intermediate-depth seismic event which has ocurred in Europe in the XXth century. The Vrancea earthquake of March 1977 (M_W = 7.4), caused widespread damage in southern and eastern Romania, as well as in Bulgaria and Republic of Moldova. Over 1500 were killed in Romania (90% of the deaths occurred in Bucharest) and the total damage caused by this earthquake exceeded 2 bill. US $. The Vrancea intermediate-depth seismic source is the major contributor to the seismic hazard in southern and eastern Romania. Therefore, due to the positioning of the 32 analyzed sites, the stochastic finite-fault simulations are performed taking into account only the Vrancea intermediate-depth seismic source. The soil conditions for the 32 analyzed sites are taken into account through the use of mean horizontal-to-vertical spectral ratios [7]. Recently, two probabilistic seismic hazard studies for Romania have been published in the literature. The first study [8] shows the results of the SHARE project and evaluated the seismic hazard for Europe, while the second study [9] deals only with the evaluation of the seismic hazard for Romania. The results from both of these two studies are used in this paper in order to evaluate the displacement response spectra from uniform hazard spectra (UHS).

2. Evaluation of soil conditions

A total of 32 sites situated in southern and eastern Romania are used in this study and their corresponding soil amplifications are employed in stochastic finite-fault simulations. The position of the 32 analyzed sites is shown in Figure 1. Also in Figure 1 are shown the positions of the 20 most populous cities in Romania according to the latest census from 2011. All of the sites can be classified as having soil classes B or C based on the criteria from

EN 1998-1 [10]. The corresponding soil conditions (shear wave velocity on the upper 30 m of soil deposits) are evaluated using the topographic slope method developed by Wald and Allen [11].

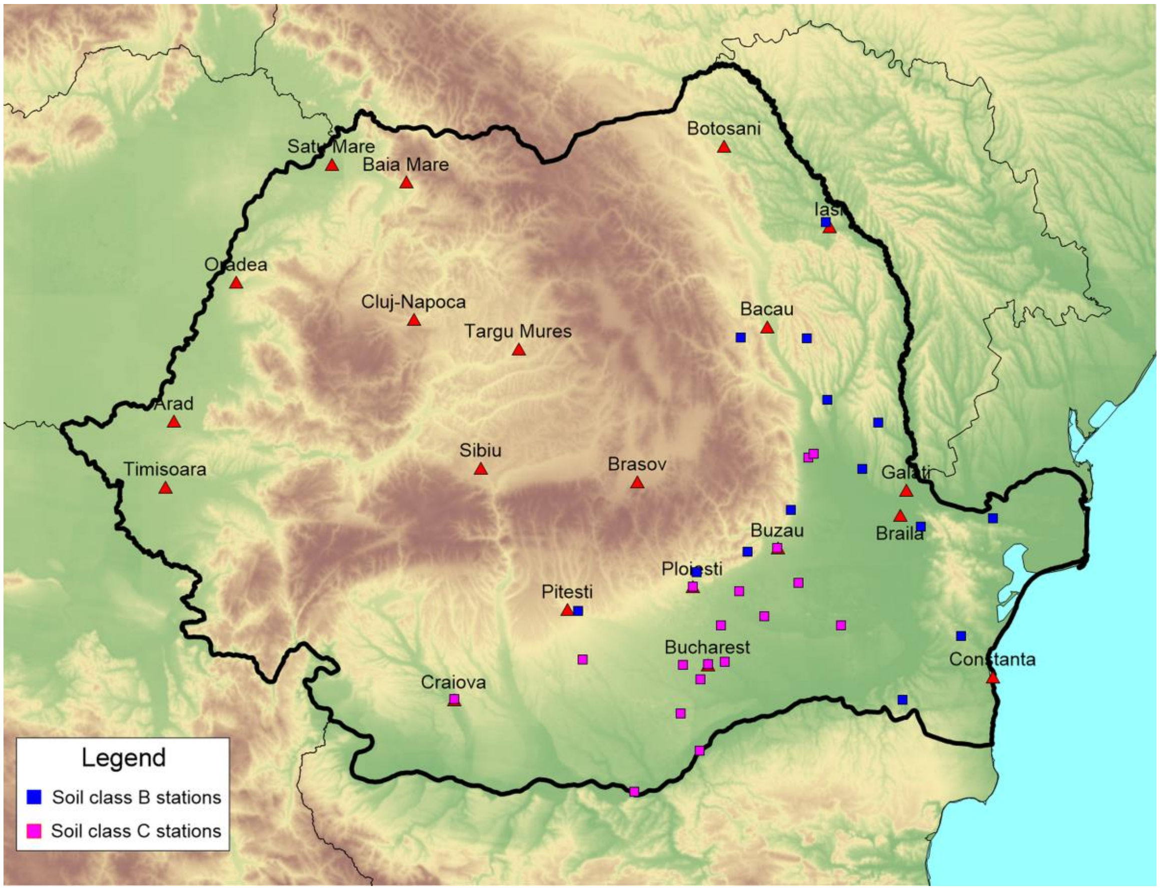

Fig. 1 – Position of the seismic stations in southern and eastern Romania for which the horizontal-to-vertical spectral ratios (HVSR) are computed. The contour of the Vrancea intermediated-depth seismic source and the epicenters of the earthquakes used in the finite-fault simulations are also shown

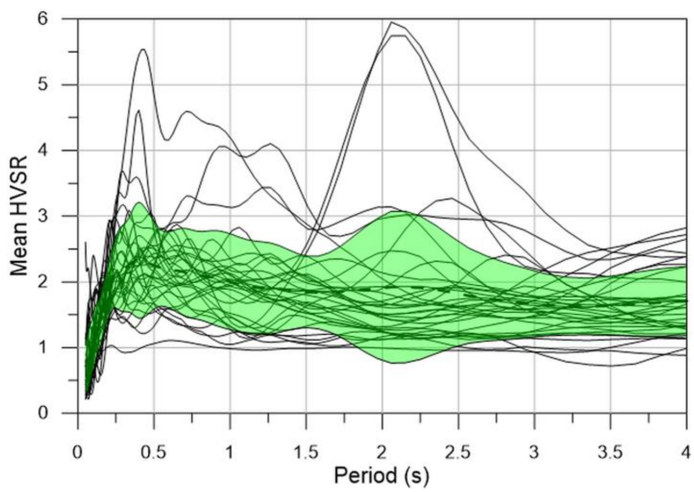

Fig. 2 – Mean HVSR curves for the 32 analyzed sites. The shaded area corresponds to the region situated in the range mean ± 1 standard deviations

Subsequently, the horizontal-to-vertical spectral ratios are evaluated for the selected sites using ground motions recorded during small magnitude ($M_W \leq 6.0$) Vrancea seismic events. All the ground motion recordings used in the computation of the HVSR curves were obtained on digital seismic instruments and the earthquakes occurred in the period 1999 – 2013. The computation of the HVSR curves was performed using the software Geopsy [12] with windows of 20 s in length. A Konno-Ohamchi [13] type smoothing (smoothing constant = 20) was applied to the signal

Figure 2 shows the mean individual curves, as well as the overall mean for all the analyzed sites. One can notice that most of the curves are situated in the region mean ± 1 standard deviations which corresponds to the shaded area in Figure 2. Nevertheless, there are some exceptions, for instance the seismic stations IAS and SCH and which show large amplifications at T = 2.0 s. Only, one seismic station, namely TIR station situated in the eastern-most part of Romania – Dobrogea which is situated adjacent to the Black Sea shows practically no amplification for the analyzed period range. In order to better evaluate the regional variation of soil conditions, the seismic stations were divided into three zones: sites situated in the southern Romania, sites situated in the eastern part of Romania and the four sites in Dobrogea. The mean HVSR curves are shown for each region in Figure 3. One can notice from Figure 3 that the long-period amplifications are much larger in the southern and eastern parts of Romania, as compared with Dobrogea region. In Figure 3, the mean HVSR for Bucharest (using data from four seismic stations) is also plotted and one can notice the relatively high amplification at T ≈ 1.0 s and other amplifications at T = 2.2 s and T > 4.0 s.

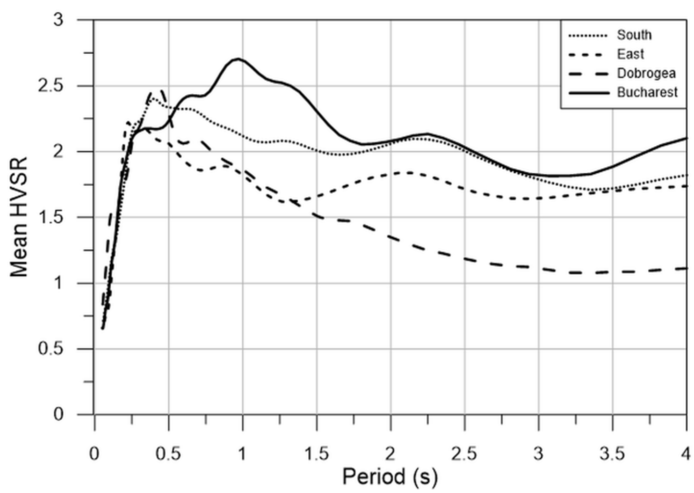

Fig. 3 – Mean regional HVSR curves

3. Evaluation of spectral displacements from stochastic simulations

The first approach used in the evaluation of spectral displacements involves stochastic finite-faults simulations performed by using the EXSIM code developed by Motazedian and Atkinson [14]. The main information regarding the simulations are taken from the paper of Pavel and Vacareanu [1] and are summarized below:

- all the earthquakes are characterized by a reverse faulting mechanism which is by far the most common focal mechanism of Vrancea intermediate-depth seismic events;
- the Q model used in the simulations is of the form $Q(f) = 100*f^{1.20}$ [15]. The geometrical spreading is taken as $1/R^{0.5}$;
- a constant stress drop of 120 bars for all the earthquakes;
- the soil conditions are taken into account through the corresponding mean HVSR curve for each site;

- 11 epicentral positions are defined for the earthquakes used in the simulations. The positions take into account the XXth century seismicity of the intermediate-depth Vrancea seismic source, as described by the ROMPLUS earthquake catalogue.
- the magnitude range of the considered seismic events is M_W = 5.5 - 7.5 (five magnitude values);
- four considered focal depths - h = 90 km, 110 km, 130 km and 150 km which cover mainly the depth domain in which most of the Vrancea intermediate-depth earthquakes occur.

Figure 4 shows the 11 epicentral positions of the earthquakes used in the simulations, as well as the contour of the Vrancea intermediate-depth seismic source as defined in the study of Pavel et al. [9]. By combining the proposed epicentral positions with the five magnitude levels and four focal depths, 141 stochastic finite-fault simulations for each site have resulted (4512 simulations in total).

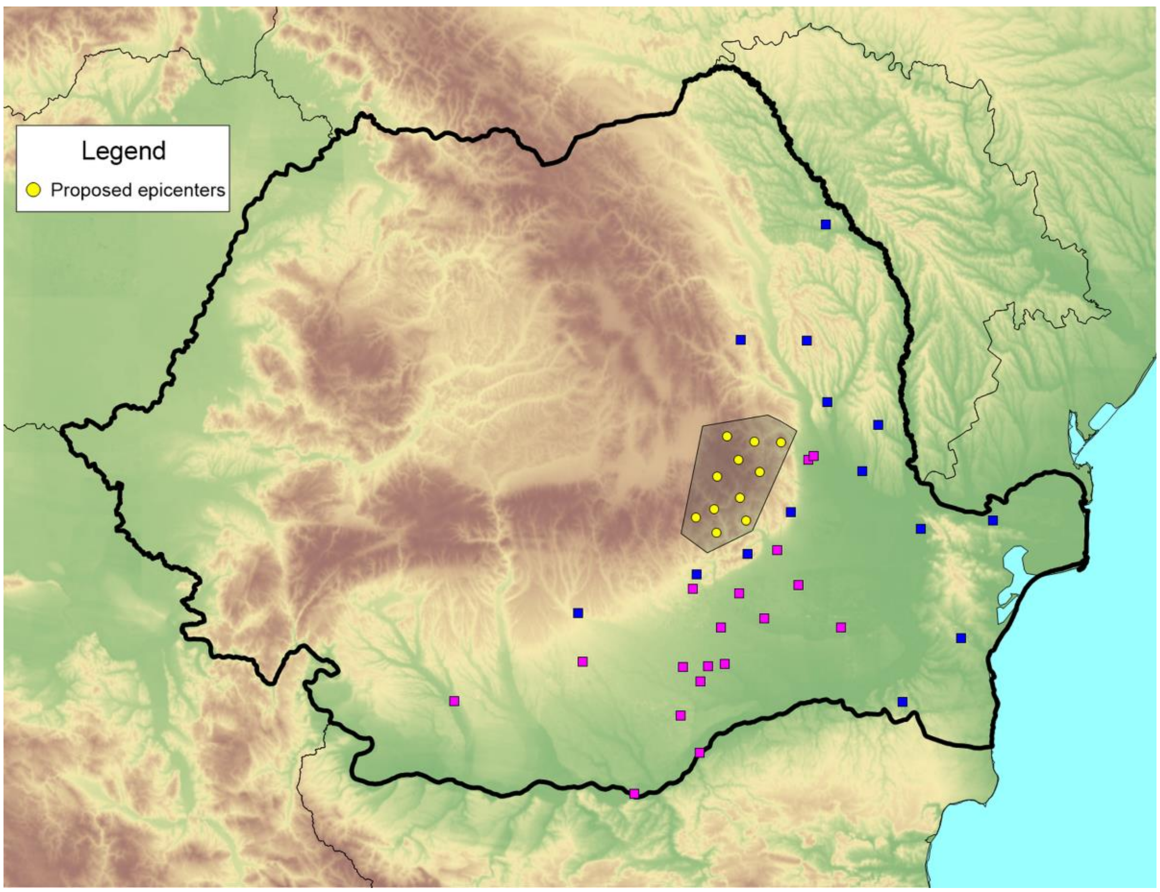

Fig. 4 – The contour of the Vrancea intermediated-depth seismic source and the epicenters of the earthquakes used in the finite-fault simulations

The influence of the earthquake magnitude on the spectral displacements is shown in Figure 5. As expected, the larger magnitude seismic events produce much larger spectral displacements and as noted by other researchers as well (e.g. Faccioli et al. [16]) the period at which the spectral displacements tend to decrease increases with the earthquake magnitude. The mean individual spectral displacements are shown in Figure 6, in which the overall mean for the 32 analyzed sites is also visible. Considerable differences between the mean individual spectral displacements can be observed for periods in excess of 0.5 s. The mean regional spectral displacements and the corresponding coefficients of variation are shown in Figure 7. Figure 7 should be read together with Figure 3 which shows the mean regional HVSR curves. One can notice that the largest spectral displacements are encountered for the southern (including Bucharest) and eastern part of Romania and the smallest values are observed for Dobrogea region. On the contrary, the largest coefficients of variation are encountered for the sites situated in Dobrogea, while for the other regions, the coefficients of variation do not exceed 0.3 thus showing a limited variability of the spectral displacements.

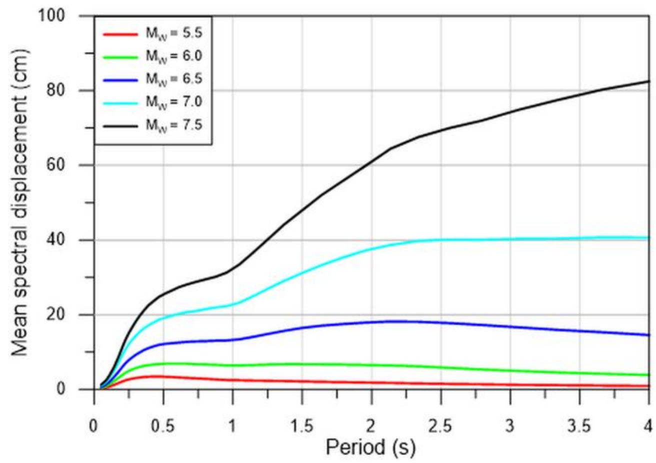

Fig. 5 – Mean spectral displacements as a function of the earthquake magnitude

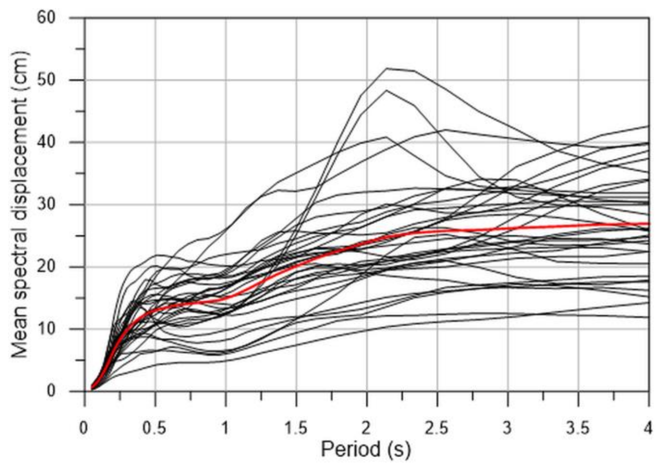

Fig. 6 – Mean spectral displacements for each individual seismic station. The overall mean spectral displacement is shown with red line

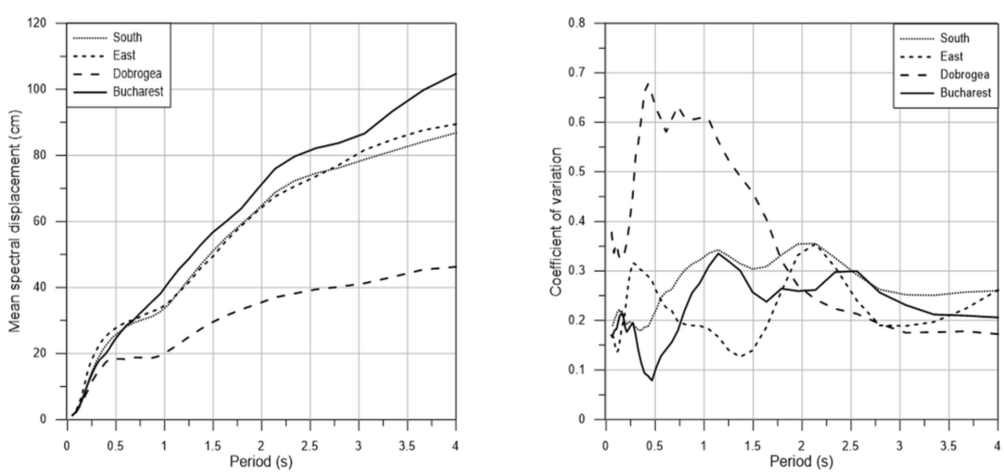

Fig. 7 – Mean regional spectral displacements (left) and corresponding coefficients of variation (right)

4. Evaluation of spectral displacements from probabilistic seismic hazard assessment

In the subsequent step of the analysis, the spectral displacements are evaluated using the seismic hazard results obtained in two studies [8, 9]. The displacements are determined from the uniform hazard spectra (UHS) for spectral accelerations. This approach of evaluating spectral displacements is similar with the one employed by Pitilakis [17] for Thessaloniki and it is used only for comparison purposes. In the first study [8], the seismic hazard is evaluated for rock conditions at a European scale (SHARE project), while in the second study [9], the soil conditions are taken into account through the use of soil classes (from EN 1998-1 [10]) inferred from the topographic slope method of Wald and Allen [11]. The results computed based on the probabilistic seismic hazard assessment performed in the study of Woessner et al. [8] are shown in Figure 8 for a mean return period of 475 years and for six selected sites (BTM, CRC, GRG, PET, PLO and URZ). The results shown in Figure 8 can’t be used in order to evaluate the spectral site-specific spectral displacements due to the fact that the reference soil conditions are taken as rock and no amplification factors are given in order to evaluate the response spectra for other soil conditions.

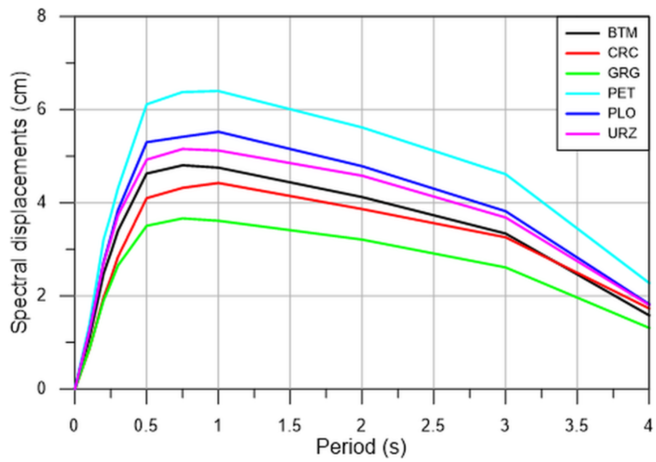

Fig. 8 – Displacement response spectra obtained for a mean return period of 475 years using the seismic hazard results of the SHARE project [8]

The current Romanian seismic design code uses a mean return period of the seismic action of 225 years. The displacement response spectra obtained from the uniform hazard spectra computed by Pavel et al. [9] are shown in Figure 9 for the six selected sites. One can notice from Figure 9 the different shape of the displacement response spectra as compared to the results from Figure 8. Nevertheless, neither the results shown in Figure 9 take into account the true soil conditions for each site. Therefore, a different approach is applied subsequently in order to incorporate the site conditions into probabilistic seismic hazard assessment. The procedure applied involved the use of the normalized acceleration response spectra obtained from the stochastic finite-fault simulations and the computation of amplification factors with respect to the amplifications given by a generic ground motion model – in this case the model of Vacareanu et al. [18] which was specifically derived for the Vrancea intermediate-depth seismic source. Thus, for different ground motion levels (peak ground accelerations), the amplification factors were computed for each site. These amplifications factors are used in the following step of the analysis in order to compute site-specific hazard with the code CRISIS developed by Ordaz et al. [19]. The probabilistic seismic hazard assessments are then performed and as previously-mentioned, the spectral displacements are obtained from the UHS for spectral accelerations. The PSHA is performed for spectral accelerations and the results for displacements are then derived. Figure 10 shows the displacement response spectra obtained using the above-mentioned procedure. The much larger values obtained in Figure 10, as compared to Figure 9 reveal the very significant influence of the soil conditions on the results. CRC and GRG stations can be defined as having short predominant periods, while the sites BTM and URZ which are situated in the Romanian Plain have several predominant periods (identified from the mean HVSR curves), including long-period spectral amplifications which can’t be captured accurately by either of the previously presented seismic hazard models.

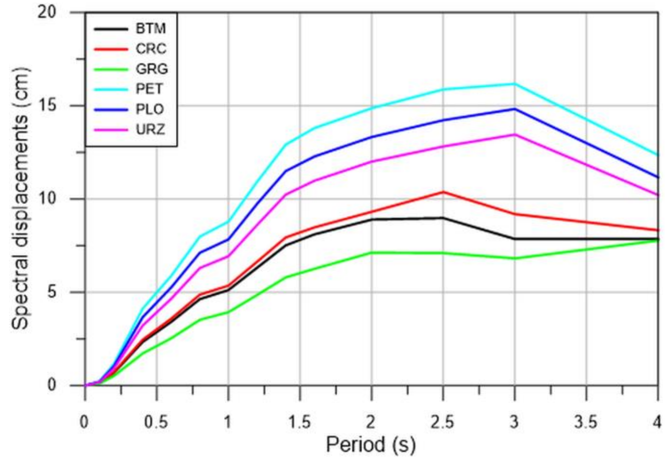

Fig. 9 – Displacement response spectra obtained for a mean return period of 225 years using the seismic hazard results of Pavel et al. [9]

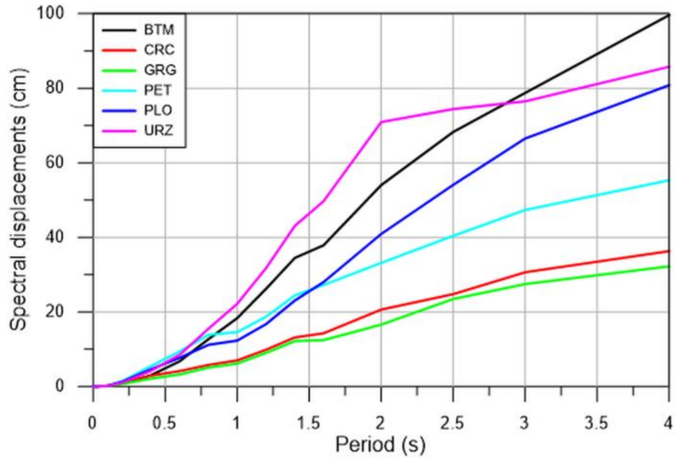

Fig. 10 – Displacement response spectra obtained for a mean return period of 225 years using the seismic hazard results of Pavel et al. [9] and the soil amplifications computed with respect to the stochastic simulations

5. Discussion of the results

In order to better evaluate the results obtained, a comparison of the results obtained from stochastic finite-fault simulations and from the probabilistic seismic hazard assessment is performed in the subsequent section for the six selected sites. In addition, the design displacement response spectra from the Romanian seismic code P100-1/2013 [2] are also shown for comparison. The results are displayed in Figure 11. One can notice from Figure 11 that the mean displacement response spectra obtained from stochastic finite-fault simulations have larger ordinates as compared to the other two types of response spectra. There is one case- namely PLO station where the spectral displacements from simulations and from seismic hazard assessment are similar. Generally, the control period T_D which marks the beginning of the constant displacement plateau is clearly marked on the curves obtained from simulations and less pronounced on the curve derived from seismic hazard assessment. For instance, a control period T_D can be observed for BTM and URZ site, while in the other cases longer T_D periods are observed. In addition, the large discrepancy between the current design displacement response spectrum for Bucharest (BTM site) and the other two spectral displacement curves is noteworthy.

Figure 12 shows the mean displacement response spectra obtained from simulations for the 32 analyzed sites for an earthquake with M_W = 7.5. The control periods T_D inferred from the mean response spectra shown in Figure 12 are in all cases above 2.0 s (with some values extending above 4.0 s). Generally, there is a tendency of increasing T_D values with the earthquake magnitude. However, there are some sites (which have clear predominant periods – IAS, SCH, MSA) where the tendency of increasing T_D values is not so evident. Nevertheless, it appears necessary to include at least one more T_D value in the future version of the Romanian seismic design code, besides the already existing values.

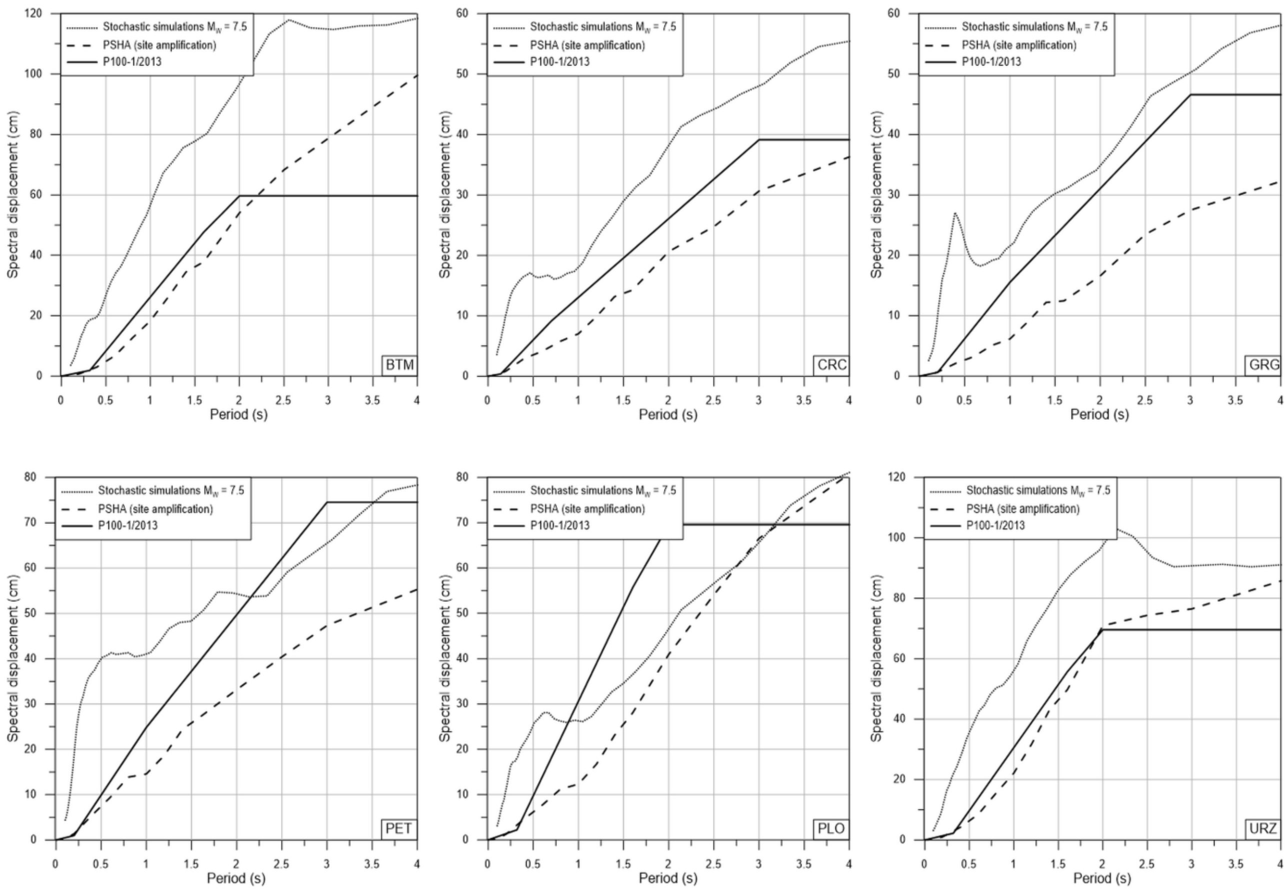

Fig. 11 – Comparison between the mean displacement response spectra obtained from stochastic simulations for M_W = 7.5, the spectral displacements obtained from seismic hazard results (with site amplifications) and the code displacement response spectra

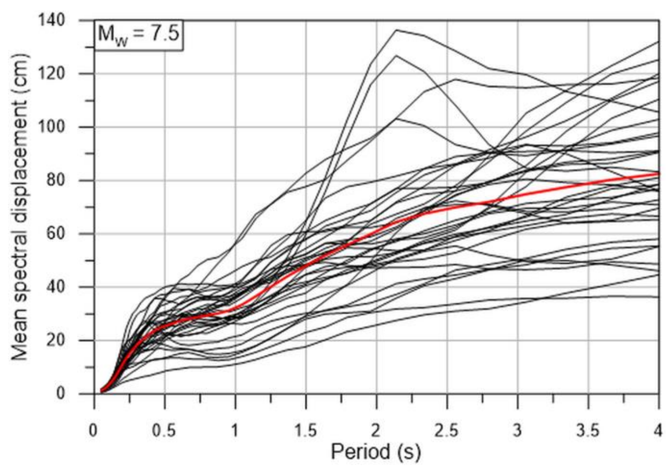

Fig. 12 – Mean spectral displacements for each individual seismic station for M_W = 7.5 earthquake. The overall mean spectral displacement is shown with red line

Based on the computed values, it appears necessary to supplement the existing database of recorded ground motions with simulated events in order to gain a better insight on the expected site-dependent spectral accelerations. Moreover, it seems necessary to extend the analysis to more seismic stations in Romania in order to evaluate the spectral displacements in other regions as well which are not under the dominant influence of the Vrancea subcrustal seismic source (e.g. Transylvania region).

Figure 13 evaluates the mean spectral displacements as a function of the earthquake magnitude for three pairs of closely spaced sites, namely the four sites in Bucharest area (BTM, CIO, CNC and MAG), two sites near Focsani (FOC and PET) and two sites near Ploiesti (PLO and SEC). One can notice that there are certain similarities between the mean displacement response spectra, especially for the two pairs of sites near Focsani and Ploiesti. In the case of Bucharest, where the inter-site distances are somewhat larger, there are significant differences especially between the site BTM on one hand and the other three sites on the other hand.

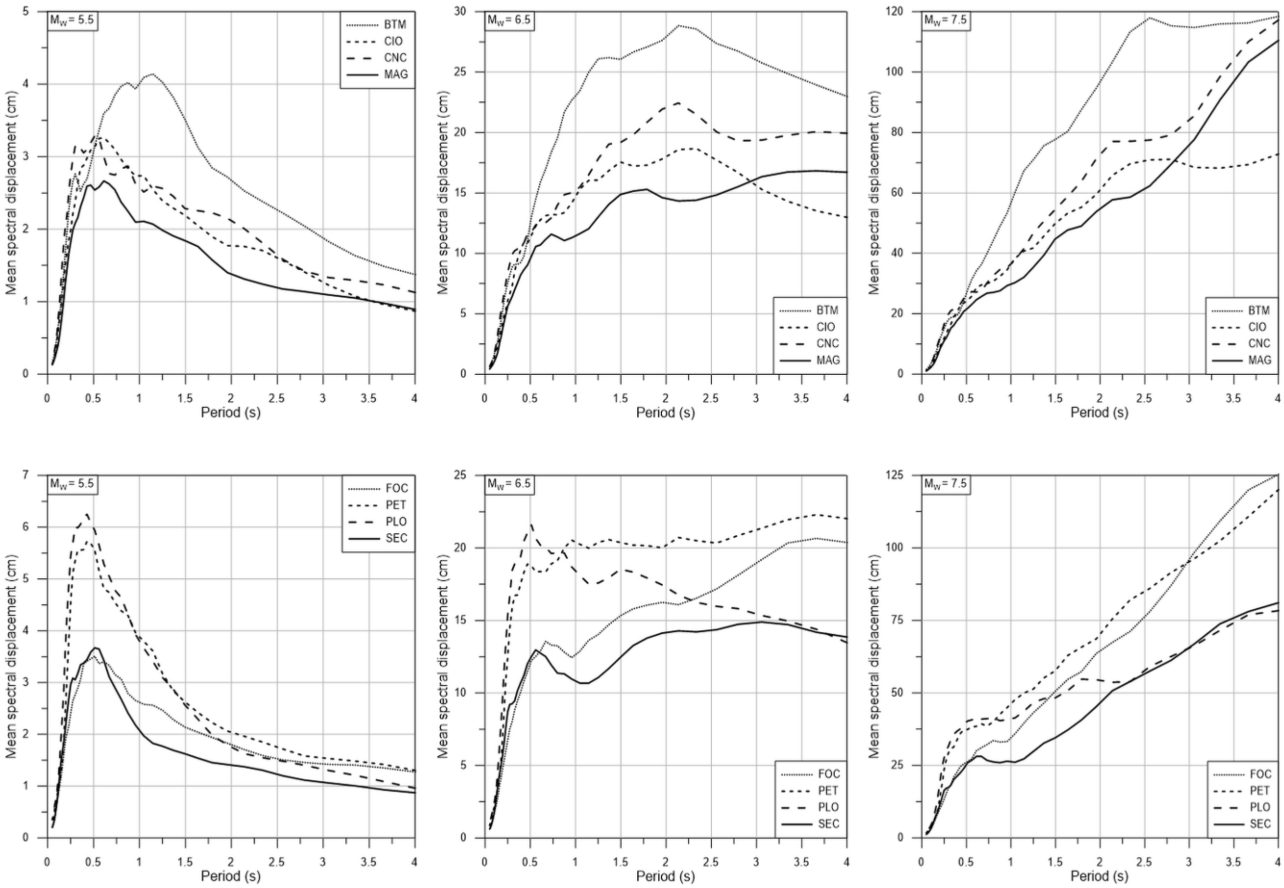

Fig. 13 – Comparison between the mean displacement response spectra obtained from stochastic simulations for M_W = 5.5, M_W = 6.5 and M_W = 7.5 for closely spaced sites in Bucharest, Focsani and Ploiesti

6. Conclusions

In this paper, an evaluation of the spectral displacements is performed for 32 sites situated in southern and eastern Romania. For each site, the soil conditions are evaluated using the horizontal-to-vertical spectral ratio technique [7]. Subsequently, the computed soil amplifications are employed in stochastic finite-fault simulations. The mean spectral displacements show a very significant influence of the earthquake magnitude on the spectral shape and an additional regional dependence. Thus, the sites situated in the easternmost part of Romania – Dobrogea, which is adjacent to the Black Sea have consistently smaller spectral displacements as compared to the other sites spread throughout southern and eastern Romania. Subsequently, the spectral displacements are evaluated using the results of two recent seismic hazard studies. The procedure involved the computation of the spectral displacements from the UHS for spectral accelerations. However, the results of the first seismic hazard model (SHARE model) do not appear as useful, at least for the moment, due to the fact that the reference soil conditions are taken as rock and no amplification factors are given in order to extend the results to other soil conditions. The results of the second study [9] were further extended in order to incorporate the site-specific soil conditions evaluated using the simulated ground motions as reference and a ground motion model derived for the Vrancea intermediate-depth seismic source [18]. It is to be emphasized the fact that PSHA is not performed for spectral displacements, since no ground motion model for displacements is available for the Vrancea intermediate-depth seismic source. More precisely, the UHS for spectral accelerations are employed in order to compute the spectral displacements (similarly with the code-based evaluation of spectral displacements). The results of the probabilistic seismic hazard assessment revealed significantly larger spectral displacements for all the analyzed sites as compared with the results previously obtained. A more in-depth evaluation of the results has revealed that in almost all cases, the mean spectral displacements obtained from stochastic simulations for a M_W = 7.5 earthquake are superior to the ones derived from site-dependent probabilistic seismic hazard assessment ad superior to the ones given by the current Romanian seismic design code [2]. The control periods T_D which represent the beginning of the constant displacement plateau were evaluated from the simulated ground motions and a magnitude-dependency of the values has been noticed in some cases (some values are above 4.0 s). However, in the case of other seismic stations which have clear predominant periods (either in the short or long period range, e.g. IAS, SCH, MSA) the magnitude-dependency of T_D is less pronounced. The comparison of mean spectral displacements between closely spaced sites has revealed certain similarities for two pairs of sites situated near Focsani and Ploiesti. Consequently, it appears necessary to supplement the existing database of recorded ground motions with simulated events which take into account the local site conditions in order to gain more information related to the combined influence of earthquake magnitude and site conditions on the spectral shapes. Due to the fact that many sites in southern Romania (including Bucharest) exhibit several predominant periods, including long-period values, possible significant long-period ordinates are to be expected in case of large magnitude Vrancea seismic events. The magnitude of these long-period ordinates might be superior to the one from the current and previous Romanian seismic design codes. Therefore, a re-evaluation of the design spectra combined with the introduction in the future version of the code of the results obtained in the most recent seismic hazard studies is envisaged as a solution to this issue.

7. Acknowledgements

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