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Conditional mean spectrum for Bucharest

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Abstract. The Conditional Mean Spectrum represents a powerful link between the seismic hazard information and the selection of strong ground motion records at a particular site. The scope of the paper is to apply for the city of Bucharest for the first time the method to obtain the Conditional Mean Spectrum (CMS) presented by Baker (2011) and to select, on the basis of the CMS, a suite of strong ground motions for performing elastic and inelastic dynamic analyses of buildings and structures with fundamental periods of vibration in the vicinity of 1.0 s. The major seismic hazard for Bucharest and for most of Southern and Eastern Romania is dominated by the Vrancea subcrustal seismic source. The ground motion prediction equation developed for subduction-type earthquakes and soil conditions by Youngs *et al*. (1997) is used for the computation of the Uniform Hazard Spectrum (UHS) and the CMS. The disaggregation of seismic hazard is then performed in order to determine the mean causal values of magnitude and source-to-site distance for a particular spectral ordinate (for a spectral period T = 1.0 s in this study). The spectral period of 1.0 s is considered to be representative for the new stock of residential and office reinforced concrete (RC) buildings in Bucharest. The differences between the Uniform Hazard Spectrum (UHS) and the Conditional Mean Spectrum (CMS) are discussed taking into account the scarcity of ground motions recorded in the region of Bucharest and the frequency content characteristics of the recorded data. Moreover, a record selection based on the criteria proposed by Baker and Cornell (2006) and Baker (2011) is performed using a dataset consisting of strong ground motions recorded during seven Vrancea seismic events.

Keywords: Vrancea seismic source; conditional mean spectrum; hazard disaggregation

1. Introduction

The major seismic hazard for the most part of Romania and for the city of Bucharest originates from the Vrancea subcrustal seismic source. Vrancea is the source of subcrustal (hypocentral depths between 60 and 170 km) seismic activity, affecting more than 2/3 of the territory of Romania and a large part of the territories of Republic of Moldova, Bulgaria and Ukraine (Lungu *et al*. 2000). The most frequent focal depths (Marmureanu *et al*. 2010) are in the range of 90 to 120 km (earthquakes in 1738, 1838, 1977) or in the range of 130 to 150 km (earthquakes from 1802,

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1940, 1986). Below 170 - 180 km in depth, the seismicity decreases abruptly. The deepest earthquake ever recorded occurred in 1982 at a depth of 218 km (M_W = 4.1), as presented by Ismail-Zadeh *et al*. (2012). The epicentral Vrancea area is confined into a rectangle of 40 × 80 km^2 (Lungu *et al*. 2000), 30 × 70 km^2 (Ismail-Zadeh *et al*. 2012) or 20 × 60 km^2 (Sokolov *et al*. 2008) having the long axis oriented on the direction N45E and centred at about 45.6^o Lat. N and 26.6^o Long. E. Another shape for the Vrancea subcrustal seismic source defined within the SHARE project is given in (Vacareanu *et al*. 2013a). Most subcrustal seismic events have a rupture propagating on the NE-SW direction, tangent to the Carpathian Mountains. The Vrancea subcrustal seismic source is surrounded towards the exterior of the Carpathian Mountains by a zone of about 7000 km^2 in which crustal earthquakes (with focal depths up to 40 km) are produced (Marmureanu *et al*. 2010).

On average 3 to 5 earthquakes of M_W > 6.5 occur each century (Ismail-Zadeh *et al*. 2012). In the 20th century seismic events having magnitudes of $M_W \geq 6.9$, occurred in October 1908 (M_W = 7.1, h = 125 km), November 1940 (M_W = 7.7, h = 150 km), March 1977 (M_W = 7.4, h = 94 km), August 1986 (M_W = 7.1, h = 131 km) and May 1990 (M_W = 6.9, h = 91 km), respectively.

The focal mechanisms of Vrancea subcrustal earthquakes are showing extension in the vertical direction and compression in the horizontal direction (Radulian *et al*. 2000). The causes of these earthquakes have not been identified with clarity and assumptions of an end of subduction process are being taken into consideration (Mocanu 2006). Probably the subducting slab is still coupled to the upper lithosphere while being pulled down by gravitational forces (Sperner *et al*. 2001). Milsom (2005) suggested that due to the movement of the Vrancea seismic zone away from the areas of recent volcanic activity, there might be a form of detachment of the subducting slab.

The conditional mean spectrum (*CMS*) was introduced by Baker and Cornell (2006). This represents, as described by the authors, "*a target spectrum that accounts for the magnitude (M), distance (R) and ε values, likely to cause a given target ground motion intensity at a given site*". Here, epsilon ε represents the number of logarithmic standard deviations by which an observed logarithmic spectral acceleration differs from the mean value of the logarithmic spectral acceleration given by a ground motion prediction equation (Baker and Cornell 2005) and it is the normalized residual between the observed and predicted values. The value of ε is given in Baker (2011):

$$\varepsilon(T) = \frac{\ln SA(T) - \mu_{\ln SA}(M, R, T)}{\sigma_{\ln SA}(T)} \tag{1}$$

where $\mu_{ln\ SA}(M, R, T)$ and $\sigma_{ln\ SA}(T)$ are the predicted mean and standard deviation of the natural logarithm of spectral acceleration at a certain period T, while ln $SA(T)$ is the natural logarithm of the observed spectral acceleration of ground motion.

According to Baker and Cornell (2005), epsilon has a significant effect on the structural response, due to the fact that it is an indicator of the spectral shape of the strong ground motion. The use of conditional mean spectrum as target spectrum for strong ground motion selection is discussed in Baker (2011). A review of current methods used in the selection of ground motion records for dynamic analyses is given by Katsanos *et al*. (2010). A critical analysis on the use of the uniform hazard spectrum (*UHS*) in the selection of ground motion records for dynamic analyses is also given in Baker (2011). The occurrence of negative ε values and its effects on the computation of the uniform hazard spectrum (*UHS*) and of the conditional mean spectrum (*CMS*) are discussed by Burks and Baker (2012). The authors mention that in the case of negative epsilon values, the conditional mean spectrum is larger than the uniform hazard spectrum, a case which is opposite to the normal relation between the two spectra.

The application of the conditional mean spectrum for several seismic sources is shown in (Ebrahimian *et al*. 2012). The authors compare the exact conditional mean spectrum with two approximate spectra for a site in the South Pars Gas Field, located in the Southern Iran. Furthermore, the authors also investigate the conditional spectrum distribution using two different approaches for disaggregation analysis.

The disaggregation of the seismic hazard (McGuire 1999; Kramer 1996; Bazzurro and Cornell 1999) allows the identification of the relative contribution to that hazard of the range of magnitudes M, source-to-site distances R and epsilons ε. An example of hazard disaggregation is given by Iervolino *et al*. (2011) for Italy. The seismic hazard and disaggregation analyses were performed for two spectral periods (T = 0 s – i.e., peak ground acceleration - *PGA* and for T = 1.0 s) and for four return periods (50 years, 475 years, 975 years and 2475 years). Furthermore, it is shown that sites close to a seismic source with high seismicity are characterized by an uni-modal disaggregation probability density function (*PDF*) and, therefore by a single design earthquake. In other cases however, there are two and even three design earthquakes caused by seismic sources situated at larger distances, able to produce large magnitude events. By using some of the above-mentioned literature references, this paper focuses on the development of a conditional mean spectrum for Bucharest (for the first time) using the most recent information (seismicity, strong ground motion, soil, etc.) collected in the BIGSEES national research project.

2. Strong ground motion data

It is well known that the main contributor to the seismic hazard for Bucharest and for over half of the territory of Romania is the Vrancea subcrustal seismic source (Lungu *et al*. 2000; Marmureanu *et al*. 2010; Sokolov *et al*. 2009). Therefore, in our paper, the seismic hazard analysis for Bucharest is performed taking into account the Vrancea intermediate-depth source only.

Table 1 Characteristics of the considered earthquakes (Romplus catalogue) and the number of seismic ground motion horizontal components

Earthquake date	Lat. N	Long. E	M_W	h (km)	No. of horizontal components
04.03.1977	45.34	26.30	7.4	94	6
30.08.1986	45.52	26.49	7.1	131	72
30.05.1990	45.83	26.89	6.9	91	87
31.05.1990	45.85	26.91	6.4	87	32
27.10.2004	45.84	26.63	6.0	105	12
14.05.2005	45.64	26.53	5.5	149	4
25.04.2009	45.68	26.62	5.4	110	4

Another reason for considering only the Vrancea subcrustal seismic source is that Bucharest is situated at considerable distances (over 60 km) from any other crustal seismic sources which could influence the level of its seismic hazard for mean return periods in excess of 100 years.

The probabilistic seismic hazard assessment is performed according to the procedure presented by McGuire (1999, 2004). Ground motion prediction models for Vrancea seismic source for peak ground acceleration have been developed in several studies, such as Lungu *et al*. (1994), Stamatovska and Petrovski (1996) and Musson (1999). Sokolov *et al*. (2008) proposed a set of ground motion prediction equations azimuth-dependent, developed for the peak ground acceleration (*PGA*), peak ground velocity (*PGV*), pseudo-spectral acceleration (*PSA*) and MSK scale seismic intensity. In the work of Delavaud *et al*. (2012) four ground motion prediction models selected within the SHARE regional project of Global Earthquake Model (GEM) are recommended for Vrancea subcrustal seismic source. Although the Vrancea subcrustal seismic source is defined (within GEM) as a non-subduction zone, the selected ground motion prediction equations corresponds to the subduction zones.

The selection of one of the four ground motion prediction models (Zhao *et al*. 2006; Atkinson and Boore, 2003; Youngs *et al*. 1997; Lin and Lee 2008) is performed according to the procedure given in Scherbaum *et al*. (2004). A strong ground motion dataset of 217 horizontal components, recorded in Romania, Bulgaria, Republic of Moldova and Serbia during seven intermediate-depth Vrancea-induced seismic events, has been selected for the analyses. The strong ground motions dataset was prepared within BIGSEES national research project. The characteristics of the seven earthquakes (date, epicentre position, moment magnitude - M_W and focal depth - h are given in Table 1 (according to the Romplus catalogue (www.infp.ro)). The numerical distribution of the 217 horizontal components for each earthquake is also given in Table 1.

The normalized acceleration response spectra for all the seismic motions recorded in the region of Bucharest during the earthquakes listed in Table 1, as well as their arithmetic mean response spectrum are plotted in Fig. 1.

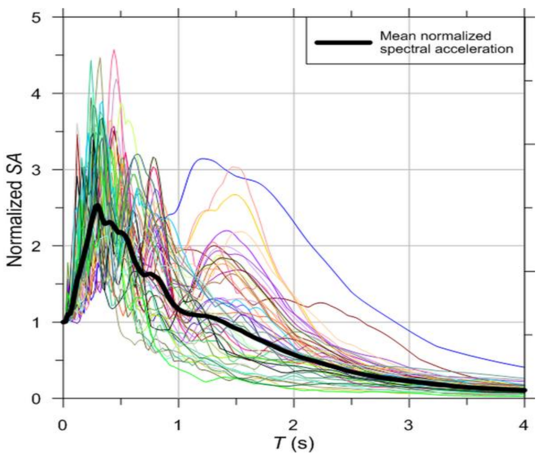


Fig. 1 Normalized acceleration response spectra for the strong ground motion recorded in Bucharest area and their mean spectrum

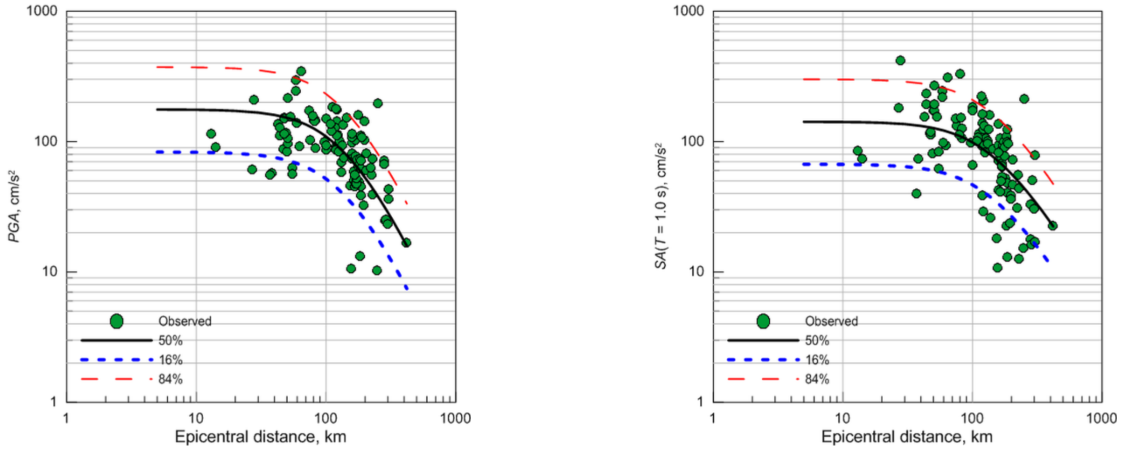


Fig. 2 Comparison of observed values with 16%, 50% and 84% predicted values using Youngs *et al.* (1997) on soil conditions PGA's for observed *PGA* values (left) and for observed *SA*(T = 1.0 s) values (right) normalized to a M_W = 7 earthquake at 100 km focal depth

Table 2 Overall statistical indicators for the Youngs *et al.* (1997) ground motion prediction equation (Vacareanu *et al.* 2013b)

Model name	*MEANNR*	σ	*MEDNR*	σ	*STDNR*	σ	*MEDLH*	σ	Grade
Youngs *et al.* (1997) - soil	0.228	0.024	0.313	0.011	0.843	0.021	0.561	0.005	B

Table 3 Statistical indicators for the Youngs *et al.* (1997) ground motion prediction equation for T = 1.0 s (Vacareanu *et al.* 2013b)

Model name	*MEANNR*	σ	*MEDNR*	σ	*STDNR*	σ	*MEDLH*	σ	Grade
Youngs *et al.* (1997) – soil	0.058	0.088	0.158	0.241	0.924	0.071	0.563	0.053	A

The grading scheme developed in Scherbaum *et al.* (2004) is based on the values of several goodness-of-fit measures. The grading ranges from D which means an unacceptable model to A- the best fitted model. The parameters used in the grading process are related to the normalized residuals: (i) the mean (*MEANNR*), median (*MEDNR*) and standard deviation (*STDNR*) of the normalized residuals or (ii) on the median of likelihood *LH* (*MEDLH*). The estimators of the parameters' standard deviation σ are obtained with "delete-1" jackknife resampling (Wu, 1986).

The overall analyses shown in (Vacareanu *et al.* 2013b) grade the Youngs *et al.* (1997) ground motion prediction equation developed for soil conditions as a grade B model for Vrancea subcrustal source. The overall values of grading parameters, as well as the values for the period T = 1.0 s are given in Table 2 and Table 3, respectively.

An extra visual check of the fit between the predicted data by Youngs *et al*. (1997) *GMPE* on soil conditions and the observed data “is provided by the normalized representation of the data, shown in the Fig. 2. The procedure described by Zhao *et al*. (2006) requires the normalization of observed data for the same seismic event. The observed data are first corrected by removing the inter-event residuals from all the observed data and then the corrected data are normalized to a generic seismic event with $M_W = 7$ produced at a focal depth $h = 100$ km.

3. Uniform Hazard Spectrum (UHS)

The Probabilistic Seismic Hazard Assessment (*PSHA*) integrates over all earthquakes and ground motions likely to occur and affect a given sitein order to estimate the mean annual frequency of exceedance of any given ground motion amplitude at that site (Bazzurro and Cornell, 1996). The *PSHA* for a site is performed by considering all the ground motions occurring from earthquakes having any possible magnitudes (ranging from lower bound magnitude to upper bound magnitude, if any) and/or source-to-site distances within the seismic source, along with their associated uncertainties. The annual frequency of exceedance γ of a given ground motion amplitude y is obtained by integrating the probabilities of all possible magnitudes and source-to-site distances and associated exceedance probabilities of ground motion amplitude y, through the total probability formula, given by the following relationship (McGuire 1999):

$$\gamma(y) = \sum_i \nu_i \int\int f_M(m) f_R(r) P[Y > y | m, r] dmdr \tag{2}$$

where ν_i is the activity rate of the seismic source i, m is the magnitude, r is the source-to-site distance and f stands for probability density function.

The probability in Eq. (2) can be further explicitly account for the ground motion randomness indicator ε, by rewriting it as follows (McGuire 1999)

$$\gamma(y) = \sum_i \nu_i \int\int\int f_M(m) f_R(r) f_e(\varepsilon) P[Y > y | m, r, \varepsilon] dmdrd\varepsilon \tag{3}$$

where ε is given by Eq. (1).

In Eq. (3), as noticed in (McGuire 1999), the probability in the integrand is, in fact, the Heaviside step function:

$$P[Y > y | m, r, \varepsilon] = H[\ln Y(m, r, \varepsilon) - \ln y] \tag{4}$$

The value is 0, if $\ln Y(m,r,\varepsilon) < \ln y$ and 1 otherwise.

The activity rate of the seismic source, above minimum magnitude is obtained as shown in (Kramer, 1996; Bazzurro and Cornell 1999; Iervolino *et al*. 2011; Sokolov *et al*. 2009; McGuire 2004):

$$\nu_i = e^{(\alpha - \beta m_{\min})} \tag{5}$$

The probability density function of earthquake magnitudes is usually considered as exponential, truncated at both, minimum magnitude M_{min} and maximum magnitude M_{max}. The probability of exceedance of a certain ground motion amplitude y, given the earthquake magnitude m, the source-

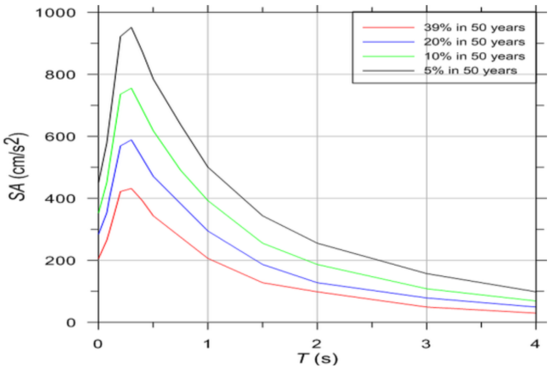


Fig. 3 Uniform hazard spectrum for Bucharest

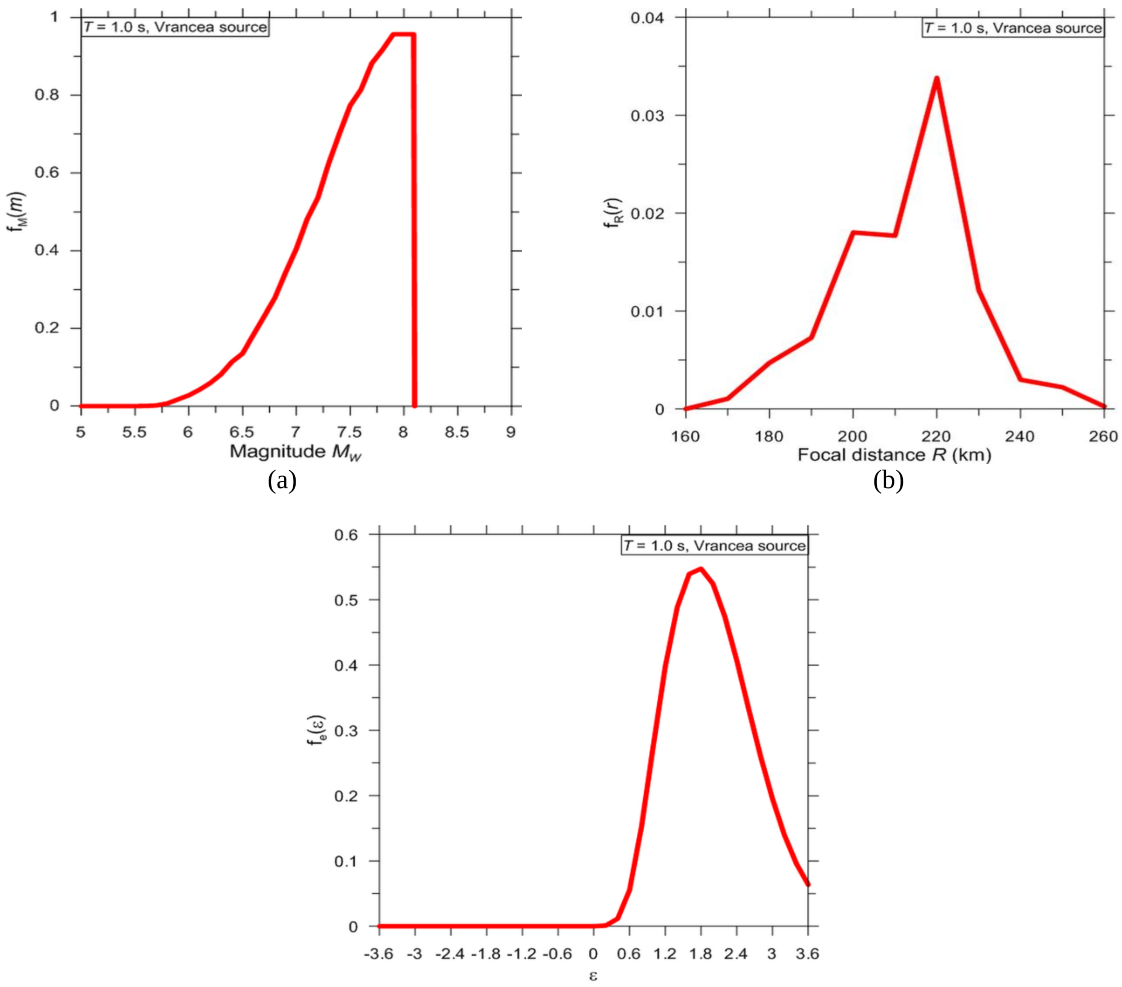
to-site distance *r* and the ground motion randomness ε is determined using the parameters provided by the ground motion prediction equations. Epsilon is considered a standard normal random variable with zero mean and unit standard deviation. The uniform hazard spectrum is obtained through *PSHA*, the spectral accelerations (*SA)* having hence, the same annual exceedance rate at each period.

The *UHS* for Bucharest-city is obtained using the earthquake catalogue (Romplus catalogue) of National Institute for Earth Physics of Romania (www.infp.ro) for the Vrancea intermediate-depth seismic source and earthquakes with $M_W \geq 5$. The minimum magnitude considered in the analysis provides the completeness of catalogue for the 20th century and the maximum magnitude taken into account in the *PSHA* is $M_{W,\max} = 8.1$ (Lungu *et al*. 2000). Based on Vrancea intermediate-depth seismic source catalogue for earthquakes from 20th century, having moment magnitudes above 5, the seismicity parameters obtained through the Maximum Likelihood Method are α = 10.3164 and β = 1.9589 (Vacareanu *et al*. 2013a). As already indicated in Chap. 2, the Youngs *et al*. (1997) ground motion prediction equation is selected for *PSHA* as shown in (Vacareanu *et al*. 2013b). The epsilon values are bounded in the range of -3.8 to + 3.8. The upper and lower bounds are determined such as to obtain similar results through the use of Eq. (2) and Eq. (3). The uniform hazard spectra given in Fig. 3 are computed for 4 different exceedance probabilities in 50 years (39%, 20 %, 10 % and 5%).

It is noted that the values of the peak ground acceleration having a probability of exceedance of 39% in 50 years and respectively 20% in 50 years are in line with the values given in the previous seismic design code of Romania, P100-1/2006 (design peak ground acceleration of 0.24*g*) and in the code in force, P100-1/2013 (design peak ground acceleration of 0.30*g*), respectively. The values of the design peak ground acceleration given in P100-1/2006 and P100-1/2013 are obtained with the same methodology described in this chapter, but the input data on seismicity and *GMPE* are different. Details on the seismicity parameters *a* and *b* for Vrancea intermediate-depth seismic source and on the used *GMPE* can be found in (Lungu *et al*. 2000).

4. Hazard disaggregation analysis

The disaggregation of the seismic hazard (McGuire, 1999) means the quantification of the contribution of each magnitude *M*, source-to-site distance *R* and epsilon ε, to the hazard of a given



(a) (b) (c)

Fig. 4. Hazard contribution to *SA* (1s) from the Vrancea intermediate-depth seismic source (a)Magnitude M_W; (b) Source-to-site distance *R*; (c) Epsilon ε.

site of interest. As presented by McGuire (1999), the hazard disaggregation is performed by dividing the cumulated annual frequencies of exceedance of a given target ground motion amplitude determined as a function of magnitude, distance and epsilon for each period to the total annual frequency of exceedance of the target ground motion amplitude. The hazard disaggregation relations are a straightforward application of Bayes' rule for conditional probabilities.

The contributions to the hazard, coming from M, R and ε for $SA(T = 1.0\ \text{s})$ computed for a probability of exceedance of 10% in 50 years for Bucharest are shown in Fig. 4 as probability density functions. The results were obtained using bins of 0.1 units for magnitude, 10 units for source-to-site distance and 0.2 units for ε, respectively.

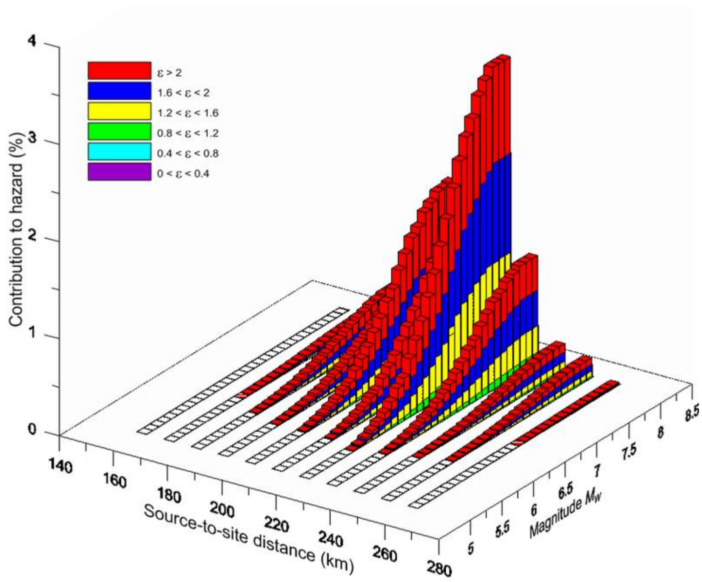


Fig. 5 Disaggregation of magnitude *M*, source-to-site distance *R* and *ε* for an exceedance probability of 10% in 50 years of the spectral acceleration in Bucharest at *T* = 1.0 s

For the spectral period *T* = 1.0 s, the mean causal magnitude is M_W = 7.46, the mean causal source-to-site distance is *R* = 212.6 km and the mean causal epsilon is *ε* = 1.98. A direct use of Youngs *et al*. (1997) ground motion prediction equation for the mean causal values produces results approximately 30% larger than the 1 sec value of *UHS*, well within the limits given in McGuire (1999).

The disaggregation of magnitude *M*, source-to-site distance *R* and *ε* for the spectral acceleration *SA*(*T* = 1.0 s) having an exceedance probability of 10 % in 50 years in Bucharest is shown in Fig. 5. As stated before, only the influence of Vrancea intermediate-depth seismic source is considered in *PSHA* and it is clear that the largest earthquakes (with magnitudes close to the maximum magnitude assigned for the Vrancea seismic source) are the largest contributors to the seismic hazard. However, these results should be treated with care, since they are obtained using only one *GMPE*.

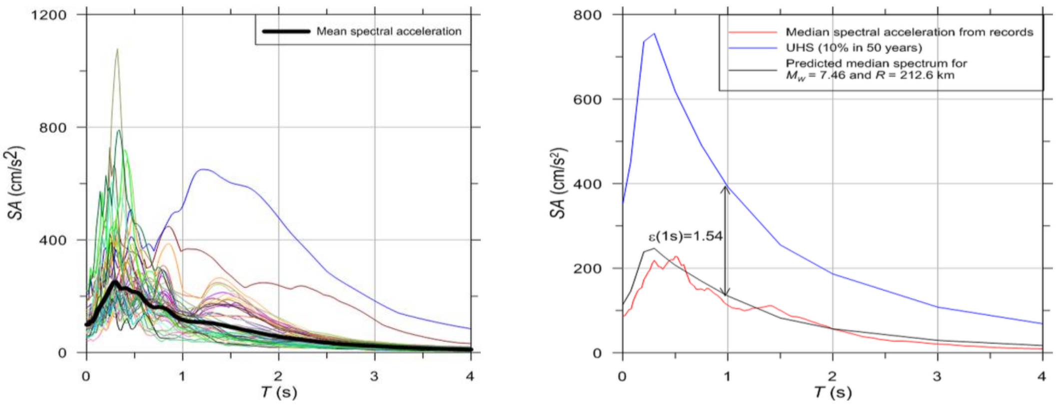
5. Conditional mean spectrum (CMS)

The absolute acceleration response spectra for the strong ground motions recorded in Bucharest area during the earthquakes listed in Table 1 and their mean spectrum are given in Figure 6a. One can notice the high variability of the frequency content of the recorded strong ground motions and the smoothness of the mean response spectrum. A comparison between the: (i) median spectrum of the geometric means of absolute acceleration spectral values of horizontal components corresponding to the ground motions recorded in Bucharest area, (ii) the uniform hazard spectrum computed for a probability of exceedance of 10% in 50 years and (iii) the median spectrum obtained with Youngs *et al*. (1997) ground motion prediction model – corresponding to mean causal values M_W = 7.46 and R = 212.6 km – is given in Fig. 6b. The actual epsilon value for T = 1.0 s period, obtained for the mean causal values of moment magnitude and source-to-site distance, is 1.54.

In Fig. 6b the similarity between the median prediction and the median spectrum for strong ground motions recorded in Bucharest area is highlighted, pointing to the accuracy of the disaggregation. The comparison between mean spectrum in Figure 6a and the median spectrum in Fig. 6b reveals very similar frequency contents, in spite of some numerical differences between these two statistical indicators.

The conditional mean values of ε at other periods T_i given the value of ε at period T* are computed using the relationship given by Baker (2011):

$$\mu_{\varepsilon(T_i)|\varepsilon(T^*)} = \rho(T_i, T^*)\varepsilon(T^*) \tag{6}$$



(a) (b)

Fig. 6. (a) Absolute acceleration response spectra for the strong ground motions recorded in Bucharest area and their mean spectrum; (b) Comparison of (i) median response spectra computed from strong ground motions recorded in Bucharest area, (ii) *UHS* (10% in 50 years) and (iii) median prediction for M_W = *7.46* and R = 212.6 km using Youngs *et al*. (1997) *GMPE*

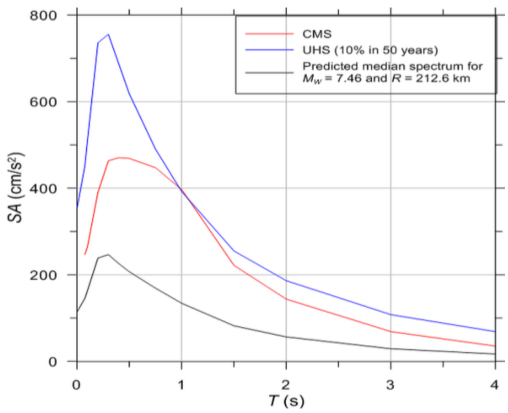


Fig. 7 *CMS*, *UHS* (10% in 50 years) and the median prediction for M_W = *7.46* and R = 212.6 km

where $\mu_{\varepsilon(T_i)|\varepsilon(T^*)}$ represents the conditional mean value of $\varepsilon(T_i)$ given $\varepsilon(T^*)$. $\rho(T_i, T^*)$ is a correlation coefficient between ε values at two periods T_i, T^* which can be computed using rel. (7) given in (Baker 2011):

$$\rho(T_{\min}, T_{\max}) = 1 - \cos\left(\frac{\pi}{2} - \left(0.359 + 0.163 I_{(T_{\min} < 0.189)} \ln\frac{T_{\min}}{0.189}\right)\ln\frac{T_{\max}}{T_{\min}}\right) \tag{7}$$

The above relationship is valid for the range of periods from 0.05 s to 5 s. T_{min} and T_{max} are the smallest and largest interest periods, while $I_{(T_{\min}<0.189)}$ is an unit-value indicator if T_{min} < 0.189 s and 0 value, otherwise. Relation (7) is derived using strong ground motions recorded from crustal earthquakes and its validity for Vrancea intermediate depth seismic source will be checked in a further study.

Eventually, the conditional mean spectrum (*CMS*) is determined with the relation given by Baker (2011) as:

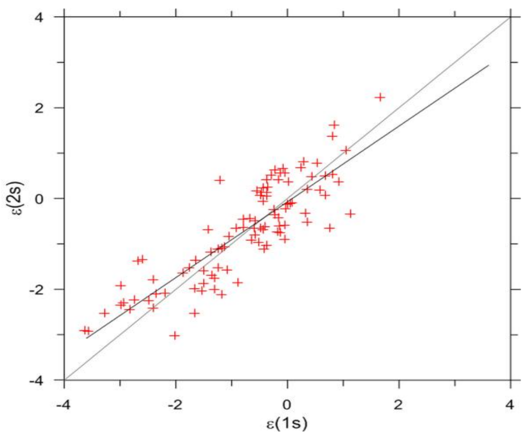
$$\mu_{\ln SA(T_i)|\ln SA(T^*)} = \mu_{\ln SA}(M, R, T_i) + \rho(T_i, T^*)\varepsilon(T^*)\sigma_{\ln SA}(T_i) \tag{8}$$

The *CMS* developed for Bucharest-city is plotted in Fig. 7 altogether with the *UHS*, for a probability of exceedance of 10% in 50 years and with the mean predicted spectrum, for M_W = 7.46 and R = 212.6 km.

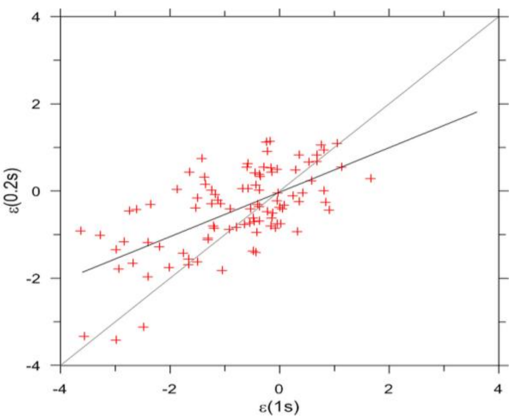
As expected, for positive epsilon values, the *CMS* falls below the *UHS* for the entire period range, except for T = 1.0 s period, where the two spectra are equal.

The correlations between ε(1s) and ε(2s) or ε(0.2s) are presented in Fig. 8 and are similar with the ones given in (Baker 2011).

It is also noticeable that the correlation between ε(1s) and ε(2s) is better than the correlation between ε(1s) and ε(0.2s). Furthermore, the slope of the trend line is lower for the second case. Both previous remarks are in line with the conclusions drawn by Baker (2011).



(a)



(b)

Fig. 8 (a) ε(1s) versus ε(2s); (b) ε(1s) versus ε(0.2s). The thick line corresponds to the actual trendline and the thin line corresponds to a perfect correlation

6. Selection and scaling of strong ground motions

Several criteria for selecting strong ground motions are given by Baker and Cornell (2006) and Baker (2011). In our paper, three criteria, mentioned below, are used for selecting strong ground motions from the dataset consisting of 217 horizontal components recorded during seven intermediate-depth Vrancea earthquakes:

I. ground motions having representative ε values for the site;
II. unscaled ground motions with the smallest *SSE* (sum of squared errors);
III. scaled ground motions with the smallest *SSE*; this criterion requires beforehand the computation of the scaling factors *SF* and then of the *SSE*.

The sum of squared errors (*SSE*) is obtained as (Baker 2011):

$$SSE = \sum_{j=1}^{n} \left(\ln SA(T_j) - \ln SA_{CMS}(T_j) \right)^2 \tag{9}$$

SSE represents the sum of differences between the logarithm of the observed strong ground motion and the logarithm of the target spectrum (in this case, *CMS*) for the period range 0.2 T_1 to 2 T_1 (Baker 2011), where T_1 = 1.0 s in this study.

The ground motion parameter ε has been identified as an indicator of spectral shape and the shape of the spectrum does not change with scaling (Baker and Cornell 2005). Therefore, the scaling procedure is applied for selecting representative strong ground motions.

The scaling factor represents the ratio of the target spectral acceleration to the actual/observed spectral acceleration of strong ground motion corresponding to the structural natural period of interest *T* as (Baker 011)

$$SF = \frac{SA_{CMS}(T)}{SA(T)} \tag{10}$$

The correlations between *SSE* and ε(1s) for both, unscaled and scaled strong ground motions, are shown in Fig. 9.

Fig. 9 a shows a strong negative correlation between the *SSE* of unscaled strong ground motions and the values of ε(1s) providing thus further evidence that epsilon is indeed a valid spectral shape indicator. On the other hand, this strong correlation vanishes for the case of scaled strong ground motion, shown in Fig. 9 b.

The use of the three selection criteria ranks the most appropriate strong ground motions for Bucharest average soil conditions considering the *CMS* for *T* = 1.0 s as target spectrum.

The top three most representative strong ground motions resulting from the application of criteria I - III are given in Table 4 and compared with the *UHS* (10% in 50 years) and *CMS*, in Fig. 10. One has to mention that since the Youngs *et al*. (1997) *GMPE* is used throughout the whole analysis, the ground motion parameter considered is the geometric mean of the horizontal components. Therefore, either both horizontal components of the strong ground motions or the geometric mean of the horizontal components given in Table 4 shall be used for performing response-history analysis. We provided three strong ground motions for each criterion since the earthquake resistant design code of Romania, P100-1/2013 allows to perform inelastic dynamic analyses using three horizontal accelerograms and to consider the most severe seismic response for design, verification or evaluation issues. Moreover, we are well aware that the seismic response

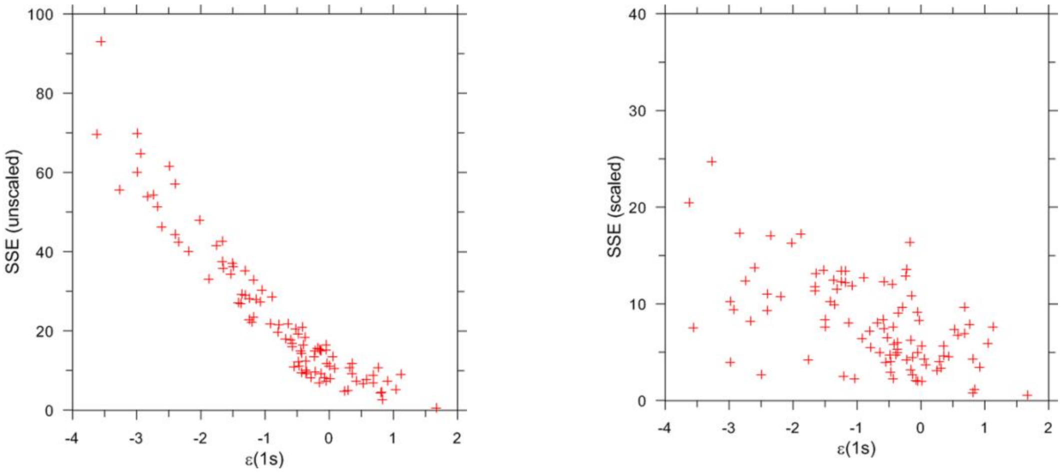
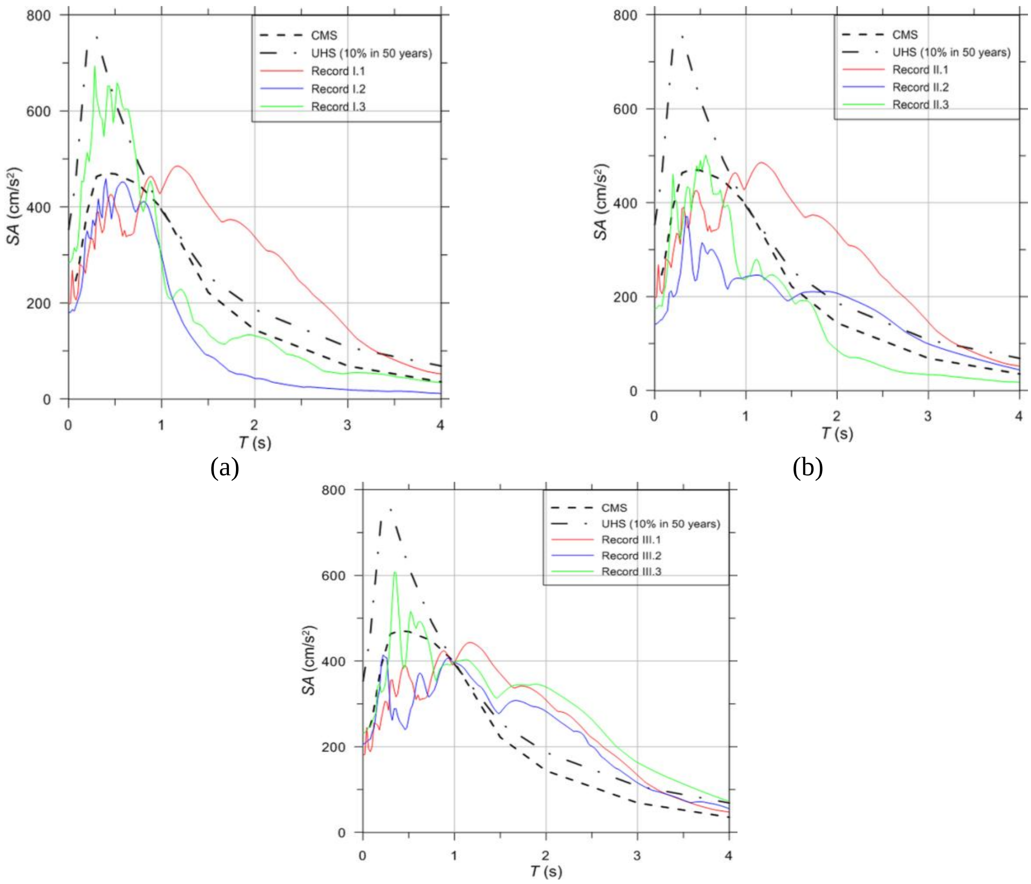


Fig. 9. a) *SSE* vs. ε(1s) - unscaled strong ground motions; b) *SSE* vs. ε(1s) - scaled strong ground motions



(a) (b)

(c)

Fig. 10 (a) Strong ground motion selection using the ε criterion; (b) Strong ground motion selection using the *SSE* criterion for unscaled records; (c) Strong ground motion selection using the *SSE* criterion for scaled records

Table 4 Most representative strong ground motion for *CMS* in Bucharest at T = 1.0 s

Strong ground motion	Criterion I	Criterion II		Criterion III
	$\varepsilon(1s)$	*SSE*	SF	*SSE*
I.1. INCERC site – record of March 4 1977	1.67			
I.2. Campina site – record of May 30, 1990	1.13			
I.3. Petresti site – record of August 30, 1986	1.05			
II.1. INCERC site – record of March 4 1977		0.50		
II.2. Ramnicu-Sarat site – record of May 30, 1990		2.58		
II.3. Valenii de Munte site – record of August 30, 1986		4.35		
III.1. INCERC site – record of March 4 1977			0.91	0.56
III.2. Ramnicu-Sarat site – record of May 30, 1990			1.66	0.82
III.3. Ramnicu-Sarat site – record of May 30, 1990			1.64	1.09

beyond the elastic limit will lengthen the period of vibration of 1.0 s considered for developing the *CMS*, but one can notice from Fig. 7 that the differences between *UHS* and *CMS* for spectral periods in excess of 1.0 s are small enough, thus providing a seismic input appropriate even for larger periods than the target one.

The *UHS*'s exceedance by the strong ground motion recorded at INCERC site for periods higher than 1.0 s (Fig. 10a and Fig. 10b) is attributable to the local soil conditions that provide higher amplifications in the long period range. The *UHS* is developed for average soil conditions and, therefore, the high amplifications for periods larger than 1.0 s shall be modelled separately in a site-dependent response spectrum based on detailed soil investigations. It is to be noted that site characterization remains a critical issue in many areas of Romania, where geophysical surveys at strong motion recording sites are necessary to be carried out for site classification purpose. Furthermore, even in Bucharest, where $V_{s,30}$ parameter is obtained for many recording sites, an alternative site classification approach should be developed since the efficiency of the $V_{s,30}$ parameter for site characterization is not proved in the cases of considerable sedimentary thickness, as for the INCERC recording site.

7. Conclusions

The main focus of this study is to investigate the applicability, for Bucharest-city, of the methodology developed by Baker (2011) in order to obtain the Conditional Mean Spectrum (*CMS*) at T = 1.0 s vibration period. The first step consists in developing the Uniform Hazard Spectrum (*UHS*) for 10% exceedance probability in 50 years based on: (i) seismicity parameters of Vrancea subcrustal source and (ii) Youngs *et al*. (1997) ground motion prediction equation. The Youngs *et al*. (1997) *GMPE* is proposed in our paper as an appropriate model for the Vrancea subcrustal seismic source, as shown in the work of (Vacareanu *et al*. 2013b). Then, the seismic hazard disaggregation methodology, presented by McGuire (1999), is also applied for the Vrancea seismic source and Bucharest. Finally, the Conditional Mean Spectrum (*CMS*), corresponding to the vibration period T = 1.0 s in Bucharest, is developed for the first time for Romania and a selection of representative ground motions is performed, as well.

The main findings from this study can be summarized as follows:

- the seismic hazard parameters are in good agreement with those given in the previous Romanian Seismic Design Code, as well as with those provided by the 2013 revised version; the values of the design peak ground acceleration given in P100-1/2006 and P100-1/2013 are obtained with the same methodology described in Chapter 3, but the input data on seismicity and *GMPE* are different. Details on the seismicity parameters *a* and *b* for Vrancea intermediate-depth seismic source and on the used *GMPE* can be found elsewhere (i.e., Lungu *et al*. 2000);
- there is a strong similarity between the values of: (i) median spectrum of the geometric means of absolute acceleration spectral values of horizontal components corresponding to the ground motions recorded in Bucharest area and (ii) the median acceleration response spectrum computed using Youngs *et al*. (1997) ground motion prediction model, for the mean causal values of the magnitude and source-to-site distance obtained through seismic hazard disaggregation; this finding confirms the accuracy of the disaggregation performed for Bucharest;
- for Bucharest-city, at the spectral period of T = 1.0 s of *UHS* absolute acceleration response spectrum having 10% probability of exceedance in 50 years, the mean causal magnitude is M_W = 7.46, the mean causal source-to-site distance is R = 212.6 km and the mean causal epsilon value is ε = 1.98; the spectral period of 1.0 s is considered as representative for a large part of the new building stock in Bucharest; in the last 10 years or so, residential buildings of 15-20 stories with dual RC structural system (moment resisting frames and shear walls) and office buildings of 8-12 stories with RC moment resisting frames came in large numbers in Bucharest and the current trend is quite similar; since the fundamental vibration period of these buildings is in the vicinity of 1.0 s, the *CMS* developed in this paper as well as the selected strong ground motions will provide a very useful tool for the elastic and inelastic dynamic analyses that are recommended by P100-1/2013 earthquake resistant design code;
- the strong negative correlation between the Sum of Squared Errors (*SSE*) and ε(1s) is also noteworthy.

The use of Conditional Mean Spectrum as target spectrum for selecting strong ground motions at other important sites in Romania, along with the analysis of the validity of relation (7) for strong ground motions recorded in Vrancea subcrustal earthquakes, are under investigation in an ongoing study.

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