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EARTH PHYSICS

ANALYSIS OF SOIL FACTOR S USING STRONG GROUND MOTIONS FROM VRANCEA SUBCRUSTAL SEISMIC SOURCE

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Abstract. A strong-ground motion database of more than 400 records from 9 intermediate-depth earthquakes with moment magnitudes M_W>5.0 was assembled and compiled for the BIGSEES national research project. These strong ground motions are used to compute the values of the soil amplification factor which is a key parameter in the definition of the elastic response spectrum defined in Eurocode 8 (EN 1998-1). The strong ground motions are divided both in accordance with the soil category of the recording stations and with the control period T_C, as well. The study of the acceleration response spectra as a function of magnitude, soil class and control period allows for the quantification of the amplification factors. Finally, the results obtained are compared with the design values from Eurocode 8 (EN 1998-1). This study comes at a time when Romania is harmonizing the national codes with the European design codes.

Key words: acceleration response spectra, epicentral distance, soil class, control period, spectral shape.

1. INTRODUCTION

The elastic response spectrum defined [7] in Eurocode 8 (EN 1998-1) is dependent on the soil class. According to EN 1998-1 [7] there are five main soil classes (or ground types as they are called in EN 1998-1) from A (rock) to E (soft soil) defined according to average shear wave velocity on the top 30 m from the surface $v_{s,30}$, or on the number of blows on the Standard Penetration Test (SPT) N_{SPT}, or according to the undrained cohesive resistance c_u.

The values of the control periods T_B, T_C and T_D and of the soil factor S for each of the five soil classes have to be defined by each country in its National Annex according to the characteristics of the earthquakes which contribute the most to the seismic hazard. EN 1998-1 [7] does not use variable soil factors with the acceleration (peak or spectral). Instead, the European code EN 1998-1 [7] proposes two types of response spectra: Type I spectra for medium and large magnitude earthquakes and Type II spectra for low magnitude earthquakes. The values of the control periods T_B, T_C and T_D and of the soil factor S given in EN 1998-1 are presented in Table 1 and Table 2. The soil factor S represents the ground motion amplification due to local soil effects with respect to the rock conditions.

Table 1

Values of parameters for Type I elastic response spectra

Soil class	S	T_B (s)	T_C (s)	T_D (s)
A	1.0	0.15	0.4	2.0
B	1.2	0.15	0.5	2.0
C	1.15	0.20	0.6	2.0
D	1.35	0.20	0.8	2.0
E	1.4	0.15	0.5	2.0

Table 2

Values of parameters for Type II elastic response spectra

Soil class	S	T_B (s)	T_C (s)	T_D (s)
A	1.0	0.05	0.25	1.2
B	1.35	0.05	0.25	1.2
C	1.5	0.10	0.25	1.2
D	1.8	0.10	0.30	1.2
E	1.6	0.05	0.25	1.2

The values given in the Tables 1 and 2 are based on the paper of Rey *et al.* [18] who used for calibration purposes the European strong ground motions. The rather low recommended values for the control period T_D at the beginning of the constant spectral displacement plateau are based on the work of Tolis and Faccioli [23], who used in their analysis strong ground motions recorded from Kobe earthquake in 1995. A comparison of the provisions of Eurocode 8 with other international seismic design codes is given in [6].

The influence of local soil conditions on the shape of the response spectra was not studied until the mid 1970s [8], when several researchers [12, 13, 22] developed spectral shapes for various soil conditions. The development of the control periods is based on the paper of Newmark and Hall [15]. A comprehensive research regarding the amplification factors using strong ground motion data recorded in Romania is shown in [11].

Generally, the main parameter used for the classification of soils is the average shear wave velocity on the top 30 m from the surface $v_{s,30}$ [2, 3]. In the Romanian seismic design code P100-1/2013 [16] the parameter that defines the soil conditions is the corner period T_C defined in Lungu *et al.* [9]. Nevertheless, as shown in numerous studies [1, 5, 17, 18, 19, 21], the elastic response spectra from EN 1998-1 [7] may differ by quite a large amount from the recorded data. In the work of Barani *et al.* [1] the authors point out that over 55% of the soil classes defined as A (rock) amplify the ground motion by a factor of more than 1.10. Nevertheless, as described in [4] the estimates of the soil factors vary accordingly to the databases of strong ground motions, method of soil classification or computation procedure.

The main focus of this paper is the quantification of the values of the soil factor S using strong ground motions recorded from Vrancea intermediate-depth earthquakes. The approach is based on the procedure described in Rey et al. [20] and Pitilakis *et al.* [17, 18]. The strong ground motion data used in the analysis are recorded from nine Vrancea intermediate-depth earthquakes having moment magnitude $M_W > 5$.

2. STRONG GROUND MOTION DATABASE

In this study a total of 233 strong ground motions (465 horizontal components) recorded from nine intermediate-depth Vrancea seismic events with moment magnitudes $5.2 \leq M_W \leq 7.4$ in over 100 seismic stations in Romania, Republic of Moldova, Bulgaria and Serbia are used. The earthquakes from the Vrancea intermediate-depth seismic source occurred between 1977 and 2009. The characteristics of these earthquakes (date, latitude and longitude of epicentre, moment magnitude M_W, focal depth h and number of strong ground motion records) are given in Table 3 (according to National Institute for Earth Physics, Romania). All the analyzed strong ground motions are collected for the BIGSEES research project and were recorded in Romania by 4 seismic networks: INFP (National Institute of Earth Physics), INCERC (Building Research Institute), NCSRR (National Centre for Seismic Risk Reduction) and GEOTEC (Institute for Geotechnical and Geophysical Studies). Only strong ground motions with peak ground accelerations (PGA) > 0.05 m/s^2 are selected in the database.

Table 3

Characteristics of the considered Vrancea intermediate-depth earthquakes

Earthquake date	Lat. N	Long. E	M_W	h (km)	No. of records
04.03.1977	45.34	26.30	7.4	109	6
30.08.1986	45.52	26.49	7.1	131	76
30.05.1990	45.83	26.89	6.9	91	91
31.05.1990	45.85	26.91	6.4	87	50
28.04.1999	45.49	26.27	5.3	151	22
27.04.2004	45.84	26.63	6.0	105	100
14.05.2005	45.64	26.53	5.5	149	30
18.06.2005	45.72	26.66	5.2	154	36
25.04.2009	45.68	26.62	5.4	110	54

The position of the 112 recording stations, as well as the corresponding soil types according to NEHRP 94 [15] are shown in Fig. 1. The soil types are considered from [24] and checked against the borehole database assembled within the BIGSEES national research project.

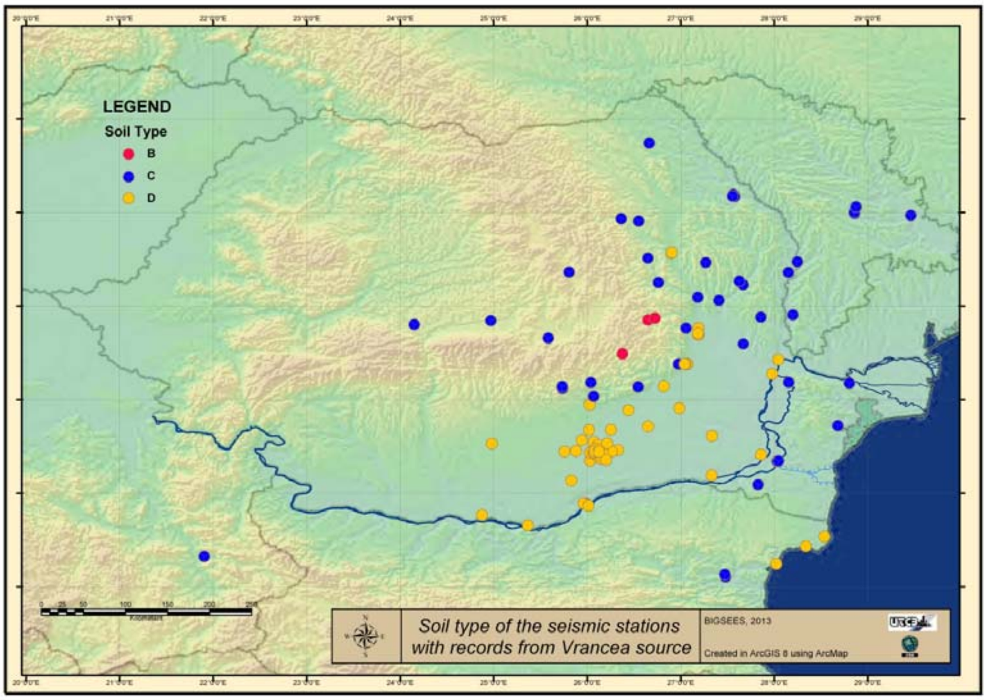

Fig. 1 – Distribution of recording seismic stations and the corresponding soil types according to NEHRP 94 [15].

The distribution of the moment magnitude M_W with the epicentral distance of the recording seismic station is shown in Fig. 2.

The statistical distribution of the maximum values of the dynamic amplification factor $(SA/PGA)_{max}$ is shown in Fig. 3 altogether with the fitted lognormal distribution.

The Q-Q plot from Figure 4 confirms the appropriateness of the use of the lognormal probability distribution for the maximum values of the dynamic amplification factor $(SA/PGA)_{max}$. The mean values and the coefficient of variations (COV) for the ratio $(SA/PGA)_{max}$ for each soil class defined according to either the Romanian seismic design code P100 or EN 1998-1 are given in Table 4 and Table 5. The B, C and D soil types from NEHRP 94 [15] are converted to A, B and C soil classes from EN 1998-1 [7].

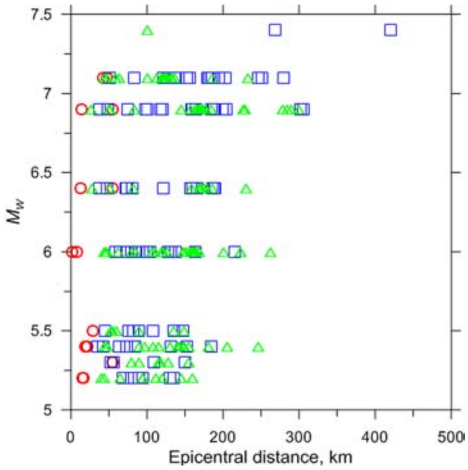

Fig. 2 – Distribution of the earthquake magnitude M_W with the epicentral distance of the recording station.

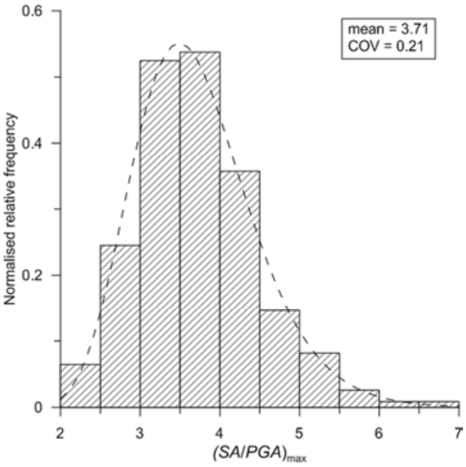

Fig. 3 – Histogram of normalized relative frequency for the maximum dynamic amplification factors $(SA/PGA)_{max}$ and fitted lognormal distribution.

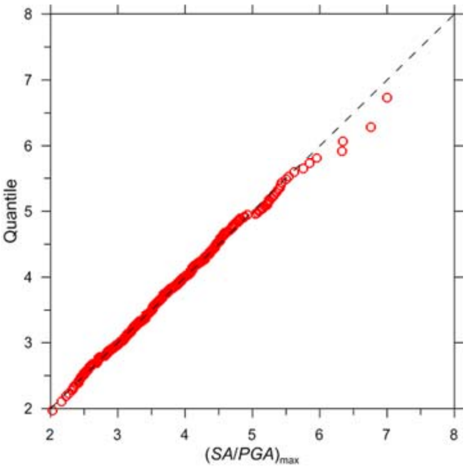

Fig. 4 –Q-Q plot for the maximum values of the dynamic amplification factor $(SA/PGA)_{max}$ given the lognormal distribution.

Table 4

Mean values and COV for $(SA/PGA)_{\max}$ values using EN 1998-1 soil conditions classification

Soil class	Mean	COV
A	3.94	0.17
B	3.82	0.20
C	3.61	0.21
All data	3.71	0.21

Table 5

Mean values and COV for $(SA/PGA)_{\max}$ values using P100-1/2013 soil conditions classification

Soil class	Mean	COV
$T_C \leq 0.7$	3.80	0.20
$0.7\text{ s} < T_C \leq 1.0\text{ s}$	3.30	0.17
$T_C > 1.0\text{ s}$	3.24	0.20
All data	3.71	0.21

From Table 4 and Table 5 one can notice the relative high mean values of $(\text{SA/PGA})_{\max}$ and the relatively constant values of the coefficient of variation. Nevertheless, the maximum values of the dynamic amplification factors do not occur at the same period. The dynamic amplification factor is called normalized spectral acceleration response values in the EN 1998-1 [7] and P100-1/2013 [16].

3. SOIL AMPLIFICATION FACTORS

3.1. GENERAL METHODOLOGY

The soil factors are computed as mentioned before using the methodology given in [17, 18, 20]. The approach is based on calculating the spectrum intensities defined in Housner [8] from the average absolute acceleration response spectra which have been previously multiplied with the source-to-site distance R. The spectrum intensities are obtained for each soil class or for each category of control period T_C values and are computed using relation (1):

$$I_{soil,rock} = \int_{0.05}^{2.5} \overline{R \cdot S_a(T)}\,\mathrm{d}T\,, \tag{1}$$

where R is the epicentral distance (source-to-site distance) and $S_a(T)$ is the spectral ordinate for vibration period T.

Next, the soil factors are obtained by dividing the values obtained on soil conditions (or softer soils) to the values obtained for rock (or harder soil) conditions, as shown in relation (2):

$$S = \frac{I_{soil}}{I_{rock}} \cdot \frac{1}{\text{SR}}\,. \tag{2}$$

The spectral ratios SR are obtained by dividing the area under the normalized acceleration response spectrum for each soil class (according to EN 1998-1) or T_C category (according to P100-1/2013) to the reference normalized acceleration response spectrum (corresponding to class A soil in EN 1998-1 and $T_C \leq 0.7$ s category for P100-1/2013). The values for SR are given in Table 6, for EN 1998-1, and in Table 7, for P 100-1/2013.

Table 6

SR values for EN 1998-1 soil conditions classification

Soil class	Type I spectrum	Type II spectrum
B	1.16	1.00
C	1.29	0.99
D	1.52	1.13
E	1.16	1.00

Table 7

SR values for P100-1/2013 soil conditions classification

Category	SR
0.7 s < $T_C \leq$ 1.0 s	1.21
$T_C >$ 1.0 s	1.43

The S values are computed separately for the ground motions divided according to the soil conditions from EN 1998-1 and for the ground motions divided according to the control period T_C from P100-1/2013. Moreover, the computations are performed using: (*i*) the entire database of ground motions and (*ii*) only the strong ground motions recorded from earthquakes with moment magnitude $M_W > 6.3$. Besides the computation of the soil factors using the method given in [17, 18, 20], the spectral shapes are also evaluated and compared with the code spectral shapes.

3.2. RESULTS

The method for the computation of the soil factors is presented in Ch. 3.1 and is applied for the ground motions divided according to the soil class and control period T_C category. Only strong ground motions from earthquakes with $M_W > 6.3$ are considered in the first stage of the analysis. Afterwards, all the strong ground motions from the database are used in the second stage of the analysis. In Fig. 5 the distance normalised median acceleration response spectra R·SA are shown separately for the soil conditions as given in P100-1/2013 [16] and EN 1998-1 [7].

The S values for the ground motions divided according to the control period T_C are given in Table 8.

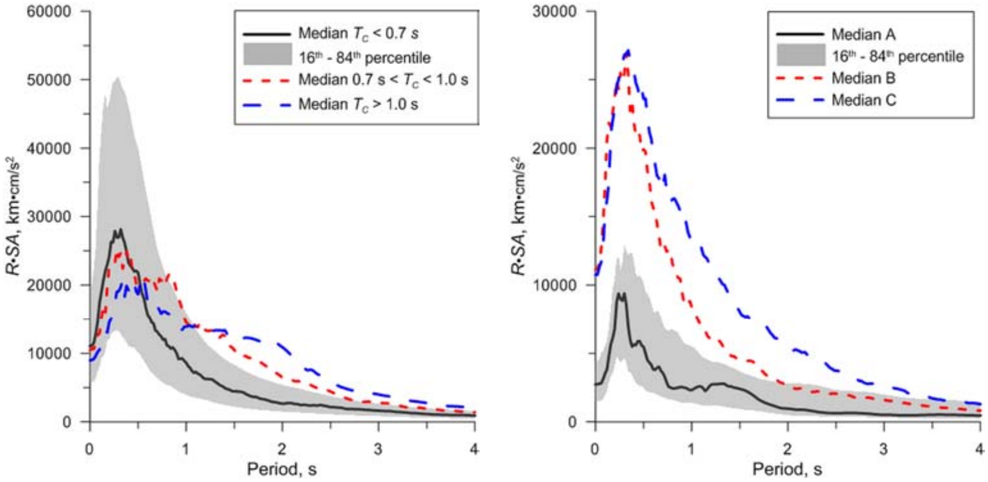

Fig. 5 – Distance normalized median acceleration response spectra for P100-1/2013 soil conditions (*left*) and EN 1998-1 soil conditions (*right*) from earthquakes with $M_W > 6.3$.

Table 8

S values for P100-1/2013 soil conditions classification

Soil category	All earthquakes	Only earthquakes with $M_W > 6.3$
0.7 s < $T_C \leq$ 1.0 s	2.05	1.03
T_C > 1.0 s	1.95	0.94

One can notice from Table 8 that the results are very much influenced by the structure of the strong ground motion database. If only the earthquakes having $M_W > 6.3$ are used, one can notice that there is practically no soil amplification. Therefore, the current definition of the design spectra from the Romanian seismic design code P100-1/2013 [16] with equal values of the maximum dynamic amplification factor for all types of soil conditions does not need soil factors ($S = 1$). However, if the database is enlarged with smaller magnitude earthquakes the values of the soil factor *S* increase up to 2. However, these results can be considered as biased due to the fact that all the strong ground motions from earthquakes with $M_W < 6.3$ have control periods $T_C < 0.7$ s. Therefore, these strong ground motions influence only this category, while the other two categories remain unchanged. Considering the small spectral accelerations of these strong ground motions, a large increase in the values of *S* occurs, a situation also reported in [17]. The *S* values for the ground motions divided according to the soil conditions from EN 1998-1 [7] of the recording station are given in Table 9.

Table 9

S values for EN 1998-1 soil conditions classification – Approach I

Soil class	All earthquakes	Only earthquakes with $M_W > 6.3$
B	3.59	2.67
C	2.97	2.63

From Table 9 one can notice the very large values of *S*, of almost similar magnitude as the ones given in [17]. These values can be explained by the very small number of seismic stations and corresponding strong ground motions belonging to soil class B. Moreover, these strong ground motions which were recorded in the epicentral region are characterised by very rapid attenuation if compared with international data. In the case we use only soil classes B and C the value of the soil factor *S* is 0.83, if all the earthquakes are considered and 0.99 in the case when only earthquakes with $M_W > 6.3$ are used (the values are obtained by dividing I_C to I_B). In order to confirm the obtained results and their appropriateness for Romania, the spectral shapes have to be checked as well.

3.3. SPECTRAL SHAPES

The spectral shapes are checked and confirmed in Figs. 6 and 7. The median spectral shapes of ground motions from earthquakes having $M_W > 6.3$ are compared with the spectral shapes from P100-1/2013 [16] in Fig. 6. One can notice from Fig. 6 that the median spectra do not exceed the code spectra for neither of the three definition of soil conditions. Moreover, the 84th percentile spectra are larger than the code spectra for a very limited spectral period range. The influence of the long-period components is visible on the median spectra for $0.7 \text{ s} < T_C \leq 1.0 \text{ s}$ and for $T_C > 1.0$ s.

The same checking is performed for the three soil classes (A, B, C) from EN 1998-1 [7]. In Fig. 7 the EN 1998-1 spectral shapes are compared with the median spectra from earthquakes with $M_W > 6.3$. It is noteworthy from Fig. 7 the fact that the code spectra lies generally between the median and the 84th percentile spectra for all three soil classes from EN 1998-1 [7]. Moreover, in the case of the soil class A, we can remark that the median and the code spectra are practically coincident. Nevertheless, the high amplifications for soil class A records (which come from the epicentral region in our database) are to be emphasized. Considering the results from Fig. 7 one can conclude that the code shapes from EN 1998-1 [7] are in good agreement with the recorded data.

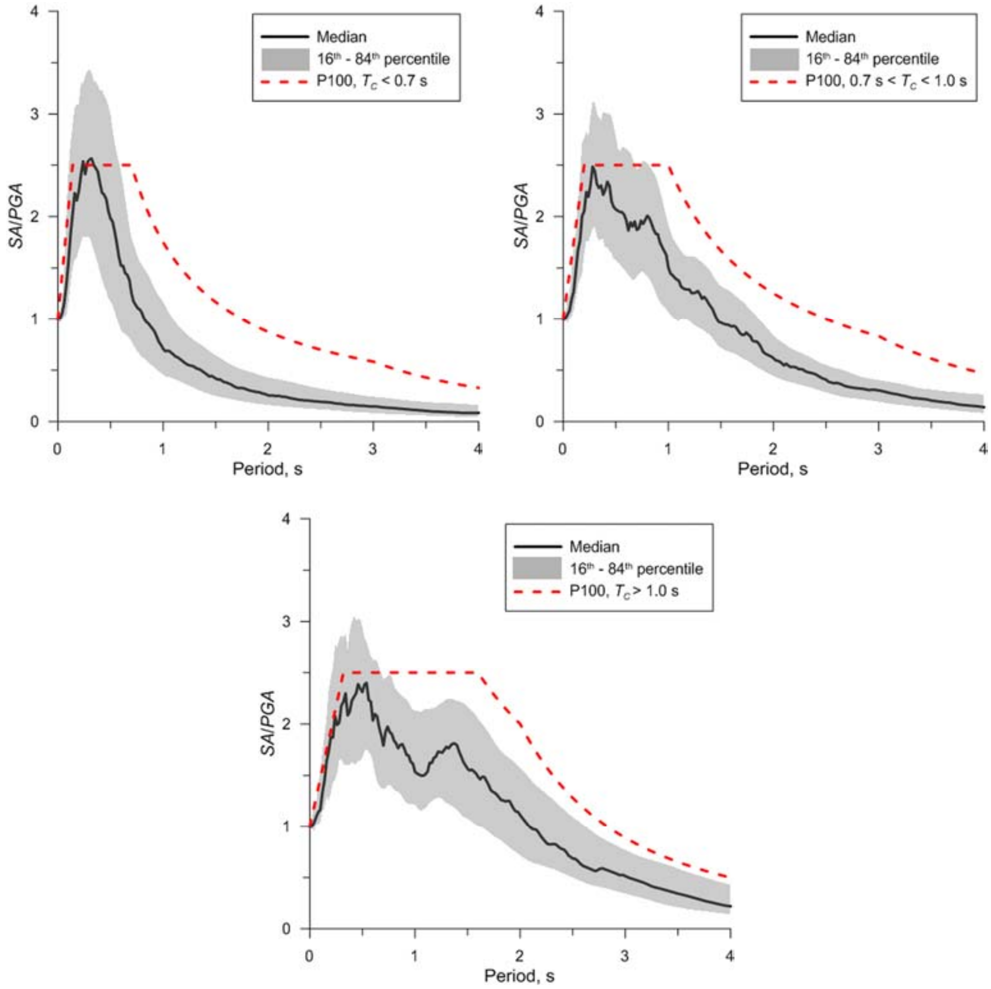

Fig. 6 – Comparison between the normalized elastic acceleration response spectra from Romanian seismic design code P100-1/2013 and the median, 16th and 84th percentile normalized acceleration response spectra obtained from earthquakes with $M_W > 6.3$.

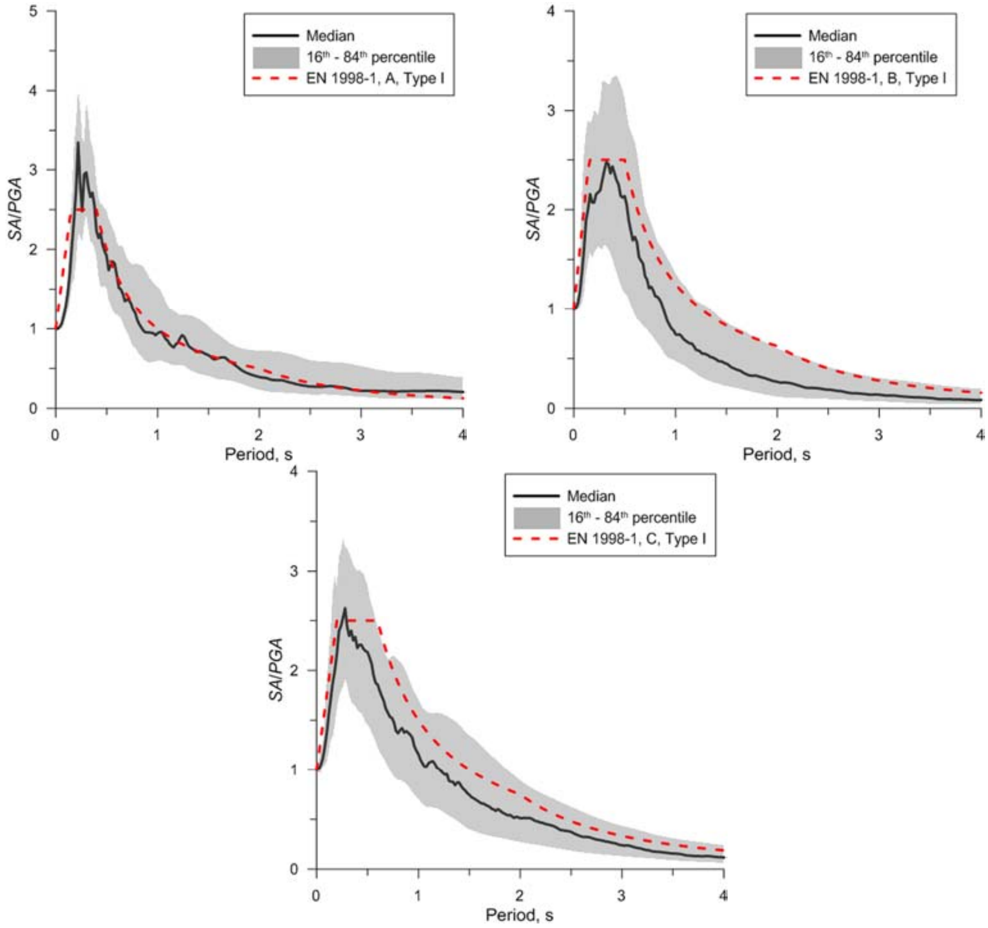

Fig. 7 – Comparison between the type I elastic response spectra from EN 1998-1 [7] for soil classes A, B and C and the median, 16th and 84th percentile normalized acceleration response spectra obtained from earthquakes with $M_W > 6.3$.

Further on, the ratios between the average spectrum intensities of the normalized acceleration response spectra for various soil conditions are also computed using the following method. The strong ground motions are divided into the same soil categories as previously. The spectrum intensities (which are not multiplied with the source-to-site distance in this case) are calculated using relation (3):

$$I = \int_{0.05}^{2.5} \overline{\left(\frac{S_a\left(T\right)}{\mathrm{PGA}} \right)} \mathrm{d}T . \tag{3}$$

The ratios between the spectrum intensities for the soil conditions definition in P100-1/2013 [16] and EN 1998-1 [7] are reported in Table 10 and Table 11, respectively.

Table 10

Spectrum intensities ratios for P100-1/2013 soil conditions classification

Soil category	All earthquakes	Only earthquakes with $M_W > 6.3$
$0.7\text{ s} < T_C \le 1.0\text{ s}$	1.50	1.18
$T_C > 1.0\text{ s}$	1.57	1.21

Table 11

Spectrum intensities ratios for EN 1998-1 soil conditions classification

Soil class	All earthquakes	Only earthquakes with $M_W > 6.3$
B	0.70	0.71
C	0.61	0.71

The ratios from Table 11 have to be considered as very much influenced by the structure of the database which has very limited data for soil class A (only records in the epicentral region with high dynamic amplification values). Finally, the results from Table 10 and Table 11 should not be regarded as *S* values, but rather as proxies for the *S* values.

4. CONCLUSIONS

The main focus of this research paper is the quantification of the values of the soil factor *S* defined in EN 1998-1 [7] for the soil conditions in Romania and using a strong ground motion database recorded from nine intermediate-depth Vrancea seismic events. The approach for the computation of the soil factor is the one presented in the papers of Rey *et al.* [20] and Pitilakis *et al.* [17]. The main conclusions of this research can be summarized as follows:

- The probability distribution of the values of the maximum dynamic amplification factor $(SA/PGA)_{max}$ can be assumed as lognormal;
- The current definition of the spectral shapes from the Romanian seismic design code P100-1/2013 does not need soil factors *S*, as all the computed values are nearly 1. Therefore, the current definition with equal values of the maximum dynamic amplification factor for all three soil categories is appropriate;
- The *S* values obtained using the definition of the soil classes from EN 1998-1 are very much influenced by the structure of the database.

Therefore, until a more complete database will be compiled with data from crustal earthquakes and additional soil profiles, the soil factors S from EN 1998-1 [7] can't be changed in the National Annex. After comparing the EN 1998-1 [7] code spectral shapes with the median spectra, it appears that they are in good agreement;

- The shift of the soil characterization parameter in the Romanian seismic design code from T_C to $v_{s,30}$ can't take place until sufficient borehole data are collected; a country-wide campaign for drilling boreholes and collecting shear wave velocity data is deeply in need.

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