Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
© 2019 Associazione Geotecnica Italiana, Rome, Italy, ISBN 978-0-367-14328-2

Preliminary revision of the seismic zonation from the current Romanian seismic design code

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ABSTRACT: Romania has one of the highest levels of seismic hazard among the European countries. Its seismicity comprises several crustal seismic sources in the central and eastern part, as well as the active Vrancea intermediate-depth seismic source. In this study, a tentative proposal for a new seismic zonation in Romania, in line with a future revision of EN 1998-1 is shown. The site classification is based essentially on the fundamental site period T_0 obtained from horizontal-to-vertical spectral ratio of ground motion recordings from seismic events with moment magnitudes $M_W \leq 6.0$. The results show that the site classification based on the fundamental site period T_0 offers information which is well corelated with the local geology and in some cases is correlated with measured data (two cases in Bucharest and Constanta). The analyses show that the largest control periods T_C occur at sites situated towards the southern part of Romania, while the largest values of spectral accelerations are obtained for sites in the vicinity of the Vrancea intermediate-depth seismic source.

1 INTRODUCTION

The current version of the Romanian seismic design code P100-1/2013 (2013) uses two main parameters for defining the site-specific design response spectrum, namely the peak ground acceleration (having an exceedance probability of 20% in 50 years) obtained from seismic hazard assessment and the control period T_C which represents the upper limit of the constant spectral acceleration plateau and which can be considered as a proxy for the evaluation of site conditions (the other control periods of the design response spectrum, namely T_B and T_D are defined in P100-1/2013 as a function of T_C). The current Romanian seismic design code was enforced in January 2013. Since the last revision, significant new information related to both seismic hazard and soil conditions have been collected in various national research projects (e.g. BIGSEES, RO-RISK, etc.). Moreover, in the light of the ongoing revision of EN 1998-1, it will be necessary to perform in the near future an updated seismic hazard assessment for Romania.

As such, this paper presents the preliminary results of a probabilistic seismic hazard assessment using reference rock conditions as it is proposed in EN 1998-1 reference combined with an updated site classification based essentially on the fundamental site period T_0 obtained using horizontal-to-vertical spectral ratio (HVSR). In this regard, ground motion recordings from more than 100 seismic stations spread throughout the territory of Romania are used. The differences between the current seismic zonation and the one proposed in this research are discussed and evaluated.

2 SITE AMPLIFICATION FACTORS

The control periods T_C and T_D from the current Romanian seismic design code P100-1/2013 are determined using the relations proposed by Lungu et al. (1997). The control periods were determined using a ground motion database of more than 100 recordings obtained during the Vrancea intermediate-depth seismic events of march 1977 (moment magnitude M_W = 7.4 and focal depth h = 94 km), August 1986 (M_W = 7.1 and h = 131 km) and May 1990 (M_W = 6.9 and h = 91 km and M_W = 6.4 and h = 87 km, respectively). Based on the analyses of the recorded ground motions, it has been observed that significant long-period spectral amplifications occur in the southern part of Romania (including Bucharest) only during the first two seismic events from March 1977 and August 1986 (events with the largest magnitude in the dataset).

Figure 1 shows the influence of the level of peak ground acceleration (PGA) on the shapes of the normalized acceleration response spectra (computed as the ratio of the spectral acceleration to the peak ground acceleration) using ground motion recordings (from Vrancea intermediate-depth earthquakes with moment magnitudes $M_W \geq 5.2$) from four regions, namely Moldova situated in the eastern part of Romania (bordering Republic of Moldova), Bucharest, Dobrogea which is the region bordering the Black Sea and Focsani situated near the epicentral region of Vrancea intermediate-depth seismic events. The results show that in the case of two regions (Moldova and Dobrogea), the influence of the peak ground acceleration on the shape of the normalized acceleration response spectra is insignificant, while in the case of Focsani and especially Bucharest, there is a net difference in the shapes of the normalized acceleration response spectra with the increase of the PGA.

The ground motion recordings from 122 seismic stations in Romania obtained during 29 crustal and intermediate-depth seismic events with moment magnitudes $M_W \leq 6.0$ are used in the analysis. The site conditions are evaluated using the fundamental site period (T_0) as proxy for site class, as proposed by Pitilakis et al. (2013, 2018) or by Verdugo et al. (2018) for Chile. The site fundamental period is obtained from the horizontal-to-vertical spectral ratio (HVSR) technique proposed by Nakamura (1989). In addition, two other criteria were used for assigning site classes, namely the local geology and the shear-wave velocity in the upper 30 m of soil deposits (Vs,30) which, because of the lack of geophysical data for most sites, was taken based on the topographic slope method of Wald and Allen (2007). A brief description of the considered site class characterization (Pitilakis et al. 2013) is given in Table 1 below.

Figure 2 shows the resulting site classes according to Pitliakis et al. (2018), as well as the position of the seismic stations employed in the analysis. One can notice that most of the sites situated in southern Romania are mainly site class C2, C3 or D sites thus highlighting the possibility of long-period spectral amplifications. This observation is also correlated with the fact that most of these sites are situated on Quaternary deposits which can be several kilometers

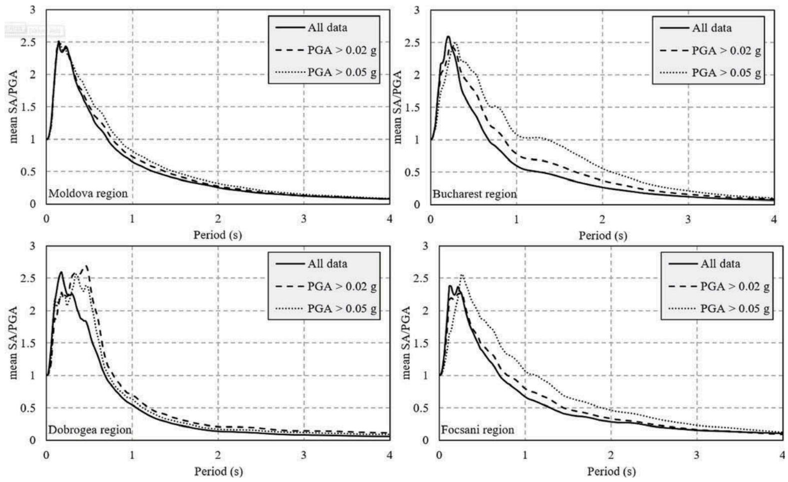

Figure 1. Normalized acceleration response spectra as a function of region and level of peak ground acceleration

Table 1. Brief description of the site characterization proposed by Pitliakis et al. (2013, 2018)

Site class	T_0 (s)	Description	Vs,30
A	≤ 0.2 s	Rock formations	≥ 800 m/s
B1	≤ 0.3 s	Soft rock formations	400 – 760 m/s
B2	≤ 0.6 s	Soil formations of very dense sand –sand gravel and/or very stiff to hard clay	350 – 500 m/s
C1	≤ 1.0 s	Soil formations of dense sand –sand gravel and/or stiff clay, of great thickness (> 60 m)	350 – 450 m/s
C2	≤ 0.8 s	Soil formations of medium dense sand – sand gravel and/or medium stiffness clay (thickness < 60 m)	250 – 400 m/s
C3	≤ 1.4 s	Soil formations of medium dense sand – sand gravel and/or medium stiffness clay (thickness > 60 m)	250 – 350 m/s
D	≤ 3.0 s	Soil formations of great overall thickness (> 60.0m), interrupted by layers of soft soils of a small thickness (5 – 15m)	150 – 300 m/s

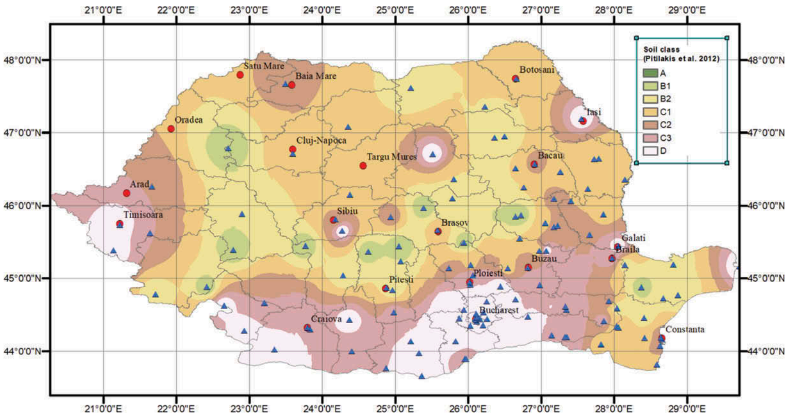

Figure 2. Site classes according to the methodology of Pitilakis et al. (2018). The seismic stations used in the analysis are marked on the map with blue triangles

deep. As such, the use of metrics related to the shear-wave velocities (e.g. $V_{S,30}$) is highly questionable as many of them are unable to capture the long-period spectral amplifications characteristic for these sites. For instance, Cioflan et al. (2009) show that the depth at which the shear wave velocity is around 800 m/s is in excess of 450 m in Bucharest, while the seismic bedrock is situated at more than 1 km in depth (e.g. Yamanaka et al. 2007, Manea et al. 2016).

In order to check the resulting HVSR against measured data, an inversion of the results obtained for INCERC station in the eastern part of Bucharest was performed in order to determine the shear-wave velocity profile which is then compared with a 150 m borehole from the same site (Calarasu, 2012). The inversion procedure was done using HV-INV which performs forward calculation and inversion of H/V spectral ratios of ambient noise (HVSRN) based on the diffuse field assumption (DFA) (García-Jerez et al. 2016). The results are illustrated in Figure 3. It is noticeable the fact that the shear-wave velocity profile obtained through inversion of the horizontal to vertical spectral ratios computed from ground motion recordings matches quite well the measured one.

Another comparison of the HVSR obtained from ground motion recordings with measured data is shown in Figure 4 in which the mean amplification factors obtained from 1D nonlinear site response analysis (using the measured shear-wave velocity profile) and from HVSR are

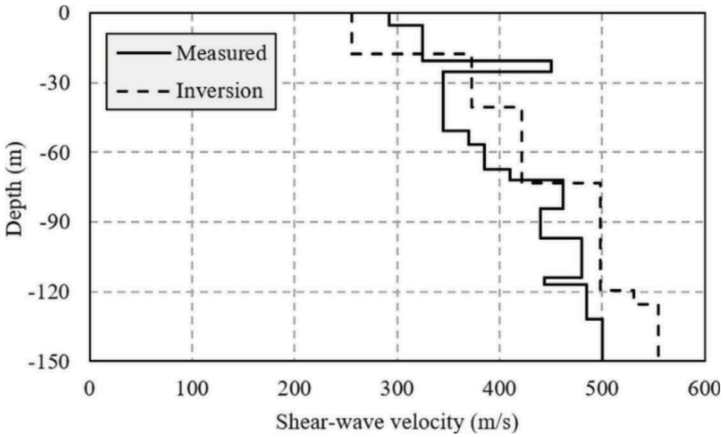

Figure 3. Comparison of measured and inferred shear-wave velocity profile for INCERC site in the eastern part of Bucharest

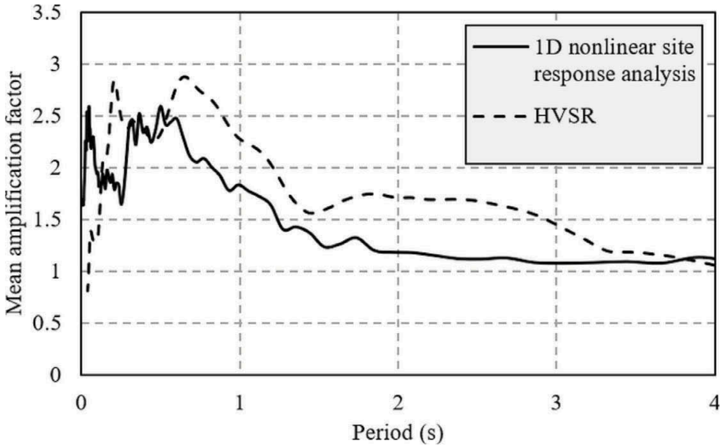

Figure 4. Comparison of mean site amplification factors for a site in Constanta obtained from 1D non-linear site response analysis and from HVSR

illustrated. It is noticeable the fact that the two mean amplification factors obtained for a site in Constanta (Dobrogea region) are similar. In addition, Pavel et al. (2019) note that the horizontal to vertical spectral ratio obtained from ground motion recordings and from ambient vibrations are reasonably well correlated in the case of Bucharest.

In the study of Pavel et al. (2019), period-dependent site amplification factors to be used for design purposes are proposed based on the methodology of Pitilakis et al. (2018) and using ground motion recordings from Vrancea intermediate-depth earthquakes. The proposed site amplifications for both short and intermediate spectral periods F_S and F_1 obtained in the study of Pavel et al. (2019) are given in Tables 2 and 3 as a function of the input peak ground acceleration for rock conditions (obtained from probabilistic seismic hazard assessment for rock conditions). The procedure for computing the site amplification is the same as in the paper of Pitialkis et al. (2018). It has to be highlighted the fact that the proposed site amplification factors are valid only for Vrancea intermediate-depth earthquakes and are different than the ones proposed by Pitialkis et al. (2018), especially in the case of the short-period site amplification factor F_S.

Table 2. Proposed short period amplification factors F_S (Pavel et al. 2019)

	PGA_{rock}				
Site class	0.1 g	0.2 g	0.3 g	0.4 g	0.5 g
A	1.0	1.0	1.0	1.0	1.0
B1	1.2	1.2	1.2	1.2	1.2
B2	1.4	1.4	1.4	1.4	1.4
C1	1.3	1.3	1.3	1.2	1.1
C2	1.2	1.2	1.1	1.1	1.0
C3	1.4	1.3	1.2	1.1	1.0
D	1.4	1.3	1.2	1.1	1.0

Table 3. Proposed intermediate period amplification factors F_1 (Pavel et al. 2019)

	PGA_{rock}				
Site class	0.1 g	0.2 g	0.3 g	0.4 g	0.5 g
A	1.0	1.0	1.0	1.0	1.0
B1	1.1	1.1	1.1	1.1	1.1
B2	1.5	1.5	1.5	1.5	1.5
C1	1.2	1.2	1.2	1.1	1.1
C2	1.3	1.3	1.2	1.2	1.1
C3	2.3	2.2	2.1	2.0	2.0
D	4.4	4.3	4.3	4.1	3.8

3 SEISMIC HAZARD ASSESSMENT

Subsequently, a revised seismic hazard assessment for Romania for rock conditions was performed in this study. The seismic sources and the seismicity parameters are taken from the work of Pavel et al. (2016). The period-dependent site amplification factors shown in Tables 2 and 3 are applied for the areas under the influence of Vrancea intermediate-depth seismic source, while in the case of the sites under the influence of local crustal seismic sources, we applied the period-dependent site amplification factors proposed by Pitialkis et al. (2018).The resulting spectral accelerations corresponding to the constant acceleration plateau of the design response spectrum were computed for all the 122 analyzed sites. Figure 5 shows the resulting map for S_s (the value corresponding to the constant spectral acceleration plateau) for a mean return period of 475 years (probability of exceedance of 10% in 50 years) with the largest values corresponding to the sites situated near the epicentral region of Vrancea intermediate-depth seismic source.

The control period T_C is computed as the ratio between the spectral acceleration at 1.0 s and the spectral acceleration corresponding to the constant acceleration plateau. The resulting map is shown in Figure 6. The map shows that the largest control periods occur in the sites situated in the southern part of Romania which were classified as having site classes C2, C3 or D.

The results of the seismic hazard assessment in terms of peak ground accelerations and control periods T_C and T_D and their comparison with the values given in the current seismic design code P100-1/2013 (2013) are illustrated in Figure 7. The control period T_D has a minimum value of 2.0 s and is computed with the relation proposed by Pitilakis et al. (2018). It is noticeable that there is an increase in the peak ground acceleration obtained from seismic hazard assessment with site amplifications, especially for the values (from P100-1/2013) in excess of 0.15 g. In the case of the control periods T_C, the values from seismic hazard

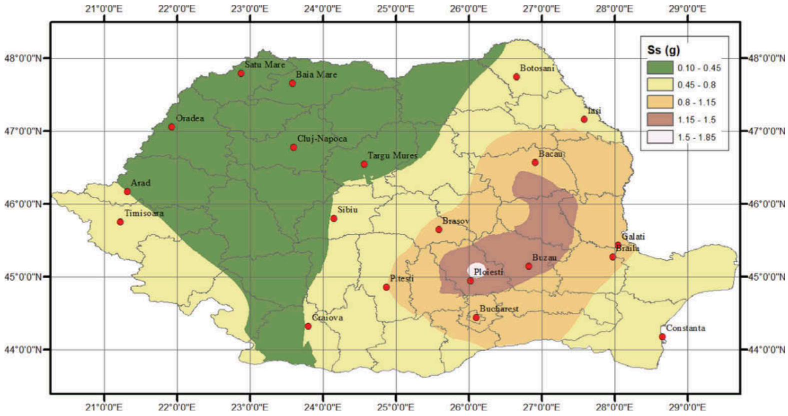

Figure 5. Territorial distribution of S_S values

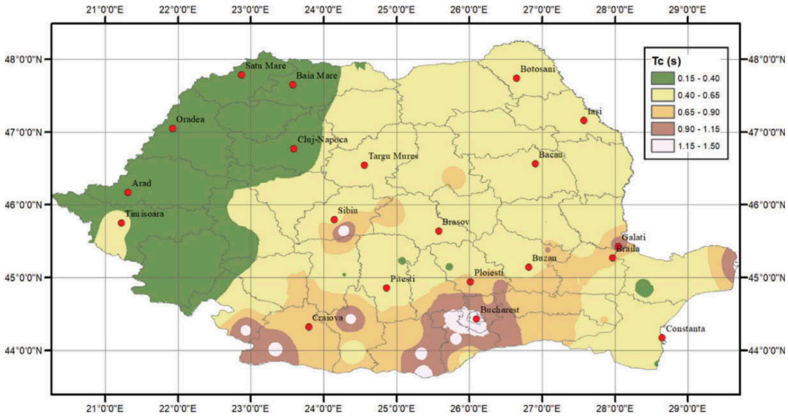

Figure 6. Territorial distribution of T_C values

assessment with site amplifications are generally smaller, while the values of the control period T_D are larger, thus the impact on the design displacement response spectra is considerable.

The variation of the control period T_C with the parameter Vs,30 (determined based on the topographic slope method of Wald and Allen (2007)) is illustrated in Figure 8. It is obvious that the largest T_C values correspond to the smallest Vs,30, but there are cases in which Vs,30 values of more than 400 m/s lead to large control periods T_C. On the contrary, small Vs,30 values (between 200 – 400 m/s) can generate control periods T_C in the range 0.3 – 0.7 s. As such, the use of site amplifications dependent on Vs,30 or on other similar metrics appears as questionable. Thus, the use of a site classification based on the fundamental site period T_0 appears as a cost-efficient method which can be applied even for the very deep soil sites from southern and eastern Romania.

Some examples of design acceleration response spectra for several cities in Romania are shown in Figure 9. Large values for the control period T_C can be observed for Ramnicu-Sarat, Bucharest or Slatina which are situated either in the vicinity of the Vrancea intermediate-depth seismic source (Ramnicu-Sarat) or in the southern part of Romania (the other two sites).

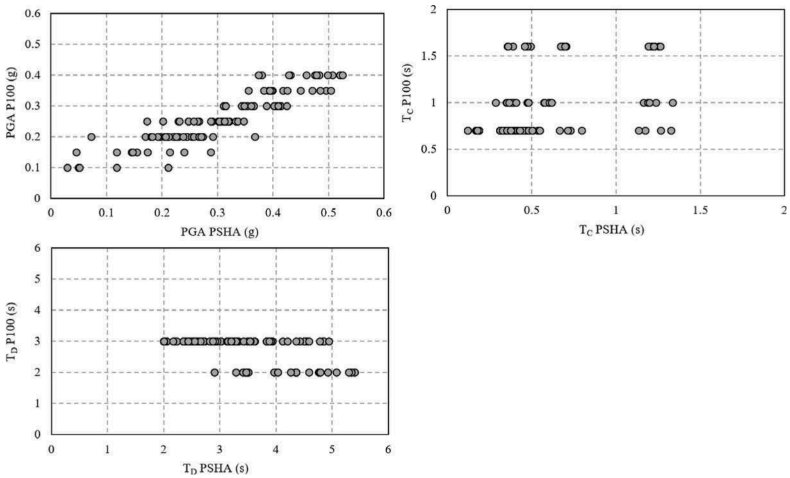

Figure 7. Comparison of peak ground acceleration and control periods T_C and T_D obtained based on seismic hazard assessment with site amplification and from the of the Romanian seismic design code P100-1/2013

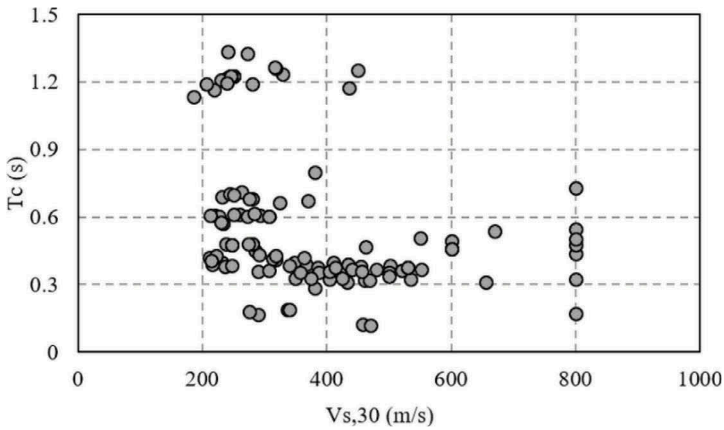

Figure 8. Variation of the control period T_C as a function of $V_{S,30}$

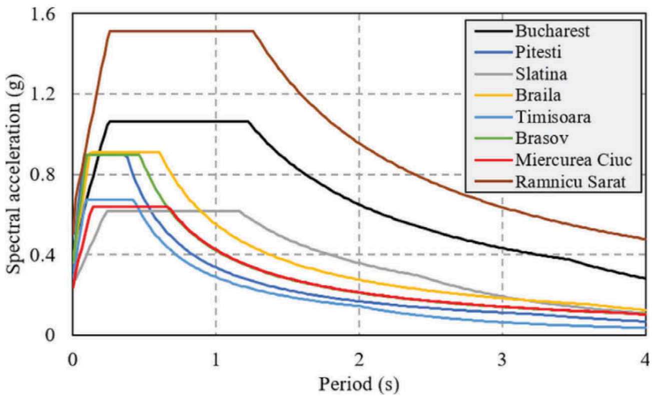

Figure 9. Examples of absolute acceleration design response spectra for several cities in Romania

4 CONCLUSIONS

In this study, a tentative proposal for a new seismic zonation of the seismic hazard in Romania is shown considering site amplification factors previously derived by Pavel et al. (2019). The analysis shows that the largest control periods T_C occur at sites situated towards the southern part of Romania. These sites, situated mainly on deep Quaternary deposits are characterized by significant long-period spectral amplifications, as observed from the horizontal-to-vertical spectral ratios (HVSR) computed from ground motion recordings of seismic events with $M_W \leq 6.0$. The results show that the site classification based on the fundamental site period T_0 offers information which is well corelated with the local geology and in some cases is correlated with measured data (the case of Bucharest or Constanta). As such, T_0 appears as a much better solution for site characterization as compared to shear wave velocity metrics (e.g. Vs,30) which, especially in the case of sites in southern Romania, appear as very unreliable for design purposes. The T_C values computed from site-dependent seismic hazard assessment are smaller than the one from the current seismic design code P100-1/2013, but the values of the control period T_D are significantly larger than the present ones. It is also to be highlighted the fact that more data (ground motion recordings, shear wave velocity profiles) are necessary to validate this proposal in order to be implemented in a future revision of the Romanian seismic design code.

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