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METHODS TO ASSESS THE SITE EFFECTS BASED ON IN SITU MEASUREMENTS IN BUCHAREST CITY, ROMANIA

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Abstract. In seismic microzonation we want to display the variation in seismic response of the subsurface and subsequently determine where the soil is being amplified to a level that may damage existing buildings or other structures. Frequently *peak ground acceleration (PGA)* is used to determine the maximum horizontal forces that can be expected. The method is not always adequate, because PGA often corresponds to high frequencies, which are out of range of the natural frequencies of most structures. The largest amplification of the soil will occur at the lowest natural frequency or its *fundamental frequency*, which corresponds to the *characteristic site period.* In situ measurements of shear wave velocity in the soil and the soil thickness, provide a direct measure of the characteristic site period. Extensively seismic noise measurements provides a more accessible method and computed *H/V* spectral ratios can also provide a good indication on the fundamental frequency of the site. Average shear wave velocity in the first 30 m depth (V_{S-30}) as defined in EUROCODE 8 and Romanian Code P100-1 is a useful indicator in seismic microzonation, showing zones with low values of average seismic velocities in Bucharest.

Key words: peak ground acceleration, characteristic site period, shear wave seismic velocity, amplification factor.

1. PEAK GROUND ACCELERATION DETERMINATION IN BUCHAREST

Bucharest is one of the most affected cities by earthquakes in Europe. Situated at 140–170 km distance from Vrancea epicentral zone, Bucharest had suffered many damages due to high energy Vrancea intermediate-depth earthquakes. For example, the 4 March 1977 event produced the collapse of 32 buildings with 8–12 levels, while more than 150 old buildings with 6–9 levels were seriously damaged. Since then the occurrence of 3 other earthquakes (1986 /*M*=7.1; 1990 /*M*=6.9; 2004 /*M*= 6.0) demonstrated that the Vrancea seismic activity is continuing, permanently threatening the Bucharest City area.

The studies done after 1977 earthquake had shown the importance of the surface geological structure upon ground motion parameters and emphasized the need for new methods of quantifying the site effects.

The earthquake of 27.10.2004 was one of the most studied as there were many good recordings in the Bucharest City area. The accelerometer network of National Institute for Earth Physics have recorded this earthquake and the PGA map for Bucharest was computed for the 3 components. Considering only the EW horizontal component, the variation in the PGA values is up to a factor 4 (16 to 60 cm/s^2) in the city area (Fig. 1). Most of this variation is due first to the package of the Quaternary sedimentary layers which amplify the original strong motion arrived from the earthquake to the bedrock.

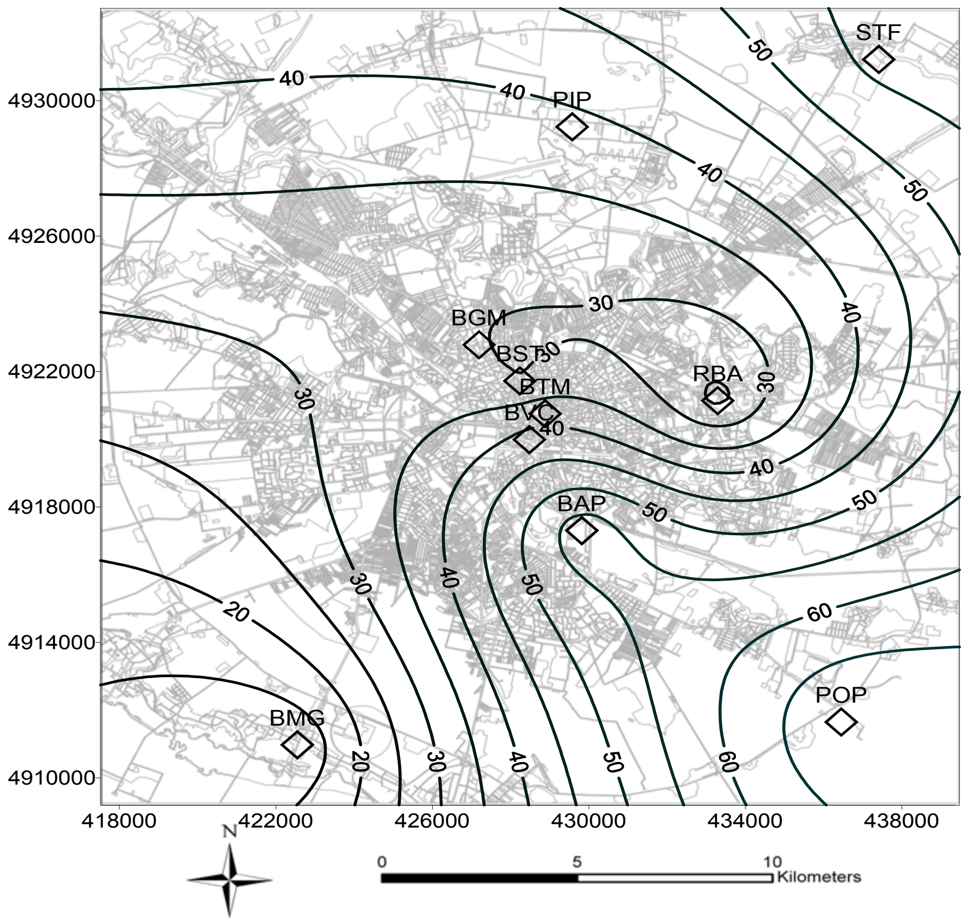

Fig. 1 – Map of the interpolated values of PGA_EW [cm/s^2] in Bucharest for the earthquake of 27.10.2004. Coordinates are in UTM. Diamond symbols represent the seismic station locations.

2. GEOLOGY OF THE BUCHAREST AREA

Bucharest City is situated in the central part of the Moesian Platform, an important structural unit of Romania which corresponds to the Romanian Plain.

The Moesian Platform has a basement with 2 structural units: a lower one with chloritic and sericitic schists of Precambrian age and an upper one made up of old Paleozoic folded marine formations going back to the Middle Carboniferous age. The sedimentary cover of the Moesian Platform is relatively thick, exceeding 6000 m. The Cretacic basement was identified at about 1000–1500 m depth and it is covered by Sarmatian and Pliocene deposits. The sea disappeared gradually and heterogeneous Tertiary and Quaternary deposits are composing the surface geology in Bucharest City area. The Tertiary formations are estimated to a thickness of about 700–800 m and they are covered by Quaternary sediments.

The cohesionless Quaternary deposits are largely developed in the Bucharest area, with thickness of about 200 m in the south to 300 m in the north (Fig. 2). The existing amount of geologic, hydrogeological and geotechnical data make possible to know the lithological succession from the bottom upwards for the Lower and Upper Quaternary deposits. They are represented in Fig. 2 by seven main lithologic complexes consisted mainly of gravel, sands and shales or clays.

The local geology above the 7-th layer, the Fratesti layer A, which is situated at 100 m depth in the south, to 200 m depth in the north, is rapidly changing from one point to another in only a few hundreds of meters (Bala et al., 2005 [1]). The real succession of the 7 principal layers as well as their physical properties can be ascribed only by in situ measurements in boreholes (Ciugudean and Stefanescu, 2006 [2]).

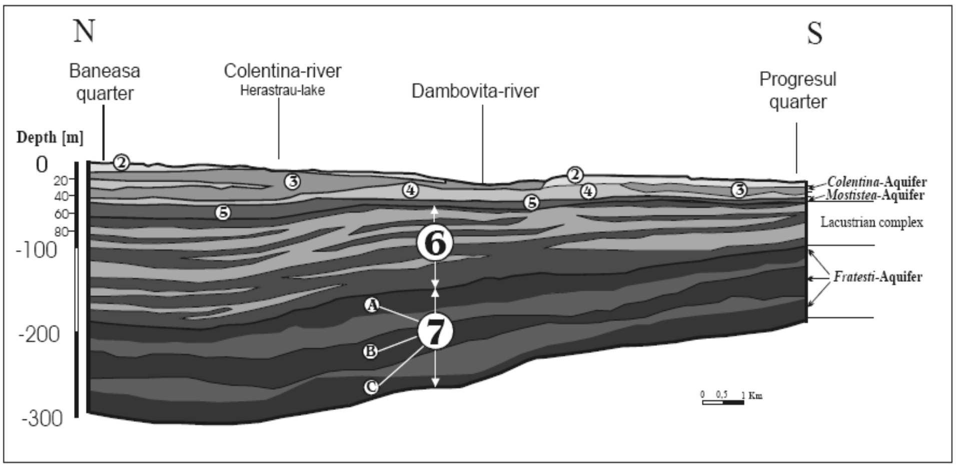

Fig. 2 – Geological cross-section in a N-S direction in Bucharest City.

3. PHYSICAL PARAMETERS OF QUATERNARY SEDIMENTARY LAYERS IN BUCHAREST

Down-hole seismic measurements were performed by a combined effort of National Institute for Earth Physics (NIEP), SC “Prospectiuni” S.A. and SC METROUL SA in 12 sites (boreholes) from Bucharest City in the frame of the CERES Project 34/2002 and CERES Project 3-1/2003. Detailed information about the measurements and seismic velocity values obtained was presented by Bala et al., 2006 [3] and Bala et al., 2007b [4].

Mean weighted values for V_p and V_s are computed for each of the 12 boreholes according to the following formula:

$$\overline{V}_s = \frac{\sum_{i=1}^{n} h_i}{\sum_{i=1}^{n} \frac{h_i}{s_i}}, \tag{1}$$

where h_i and V_{Si} denote the thickness (in meters) and the shear-wave velocity (in m/s) of the *i*-th layer, in a total of *n* layers, existing in the same type of stratum (Romanian Code for the seismic design for buildings – P100-1/2006 [5] and EUROCODE 8 [6]).

The site Bazilescu was excluded from presentation due to low velocities recorded in all the layers, for which a satisfactory explanation was not yet found. However in a recent paper (Hannich et al., 2006 [7]) seismic measurements using SCPTU techniques are presented for the same site (BAZI) and low V_s values are presented of about 250 m/s at 26 m depth, with a large drop (150 m/s) between 7–11 m depth. This confirmation of low velocity of the shear waves in the same site put into evidence by another method will lead us to reconsider our measurements in Bazilescu site.

The National Center for Seismic Risk Reduction (NCSRR, Bucharest) instrumented in 2003 seven sites in the northern half of Bucharest City (Aldea et al., 2006 [8]) in cooperation with the Japan International Cooperation Agency (JICA). NCSRR performed downhole seismic measurements at all sites that were instrumented, the deepest investigation going down to 140 m depth. All the results of the mean weighted seismic velocities until 28–30 m depth (Aldea et al., 2006 [8]) are gathered in the Table 1.

Other shear wave velocity values were obtained in the frame of the NATO SfP Project 981882 in the years 2006–2007 and they were reported by Bala et al., 2007a [9]and Ritter et al., 2007 [10].

3.1. CHARACTERISTIC SITE PERIOD

The largest amplification of the soil will occur at the lowest natural frequency or its *fundamental frequency*. The period of vibration corresponding to the fundamental frequency is called the *characteristic site period* (see Eq. 2). The characteristic site period, which only depends on the soil thickness and average shear wave velocity of the soil, provides already a very useful indication of the period of vibration at which the most significant amplification can be expected.

Using the velocity data from 8 of the boreholes of the 12 presented by Bala et al., 2007b [4], the map from Fig. 2 was computed according to the formula:

$$T = 4h/V_s, \tag{2}$$

in which T = characteristic site period in seconds and V_S is the average velocity until the Fratesti layer and h is the total thickness of the sedimentary layers.

The characteristic site period was computed with h being the total thickness of the main geologic layers until the 7-th layer (Fratesti Layer, described by Ciugudean and Stefanescu, 2006 [2]). V_s is computed as mean weighted velocity value down to the same geologic layer for each of the 8 sites. Only in these sites the depth of the borehole intercepted the upper surface of Fratesti layer considered as bedrock.

The map from Fig. 3 shows an increase in the characteristic site period, from 1.25 s in the south (NIEP-Magurele) to 1.75 s in the north (Otopeni site), due to the general increase of the depth to Fratesti Layer from south to north. In the meantime due to the different values of mean weighted velocity for each site, some variations in the characteristic site period appear right in the central part of Bucharest, which is the most sensible zone vulnerable to strong seismic events.

A similar computation was made by Mandrescu et al., 2004 [11], which considered the same interface as bedrock (Fratesti layer). In their map of the predominant period, values of 1.0 s in the south to the 1.9 s in the north of Bucharest are computed by interpolation. Computations are made on the depth values obtained from technical boreholes, but the shear wave velocity values are assumed from literature.

The H/V ambient vibration method (*Nakamura's technique*) has become in the last two decades one of the most popular methods for estimating site response in urban areas. For the city of Bucharest, Bonjer et al., 1999 [12] applied this technique for 16 sites. They found a remarkable similarity of the H/V curves between 0.1 to 10 seconds. The period of the identified resonance peaks varies in a narrow band from 1.2 to 1.6 seconds with an average value of $T = 1.36 \pm 0.14$.

In the paper of Zaharia et al., 2008 [13] the H/V ratios computed for 22 sites in Bucharest area and the results also show a clear peak in all ratios of which period varies from 0.99 to 1.85 seconds. The average period of these peaks is $T = 1.47 \pm 0.20$ seconds. This period correlates well with the fundamental period computed when we consider one layer overlying the half-space (Fratesti complex).

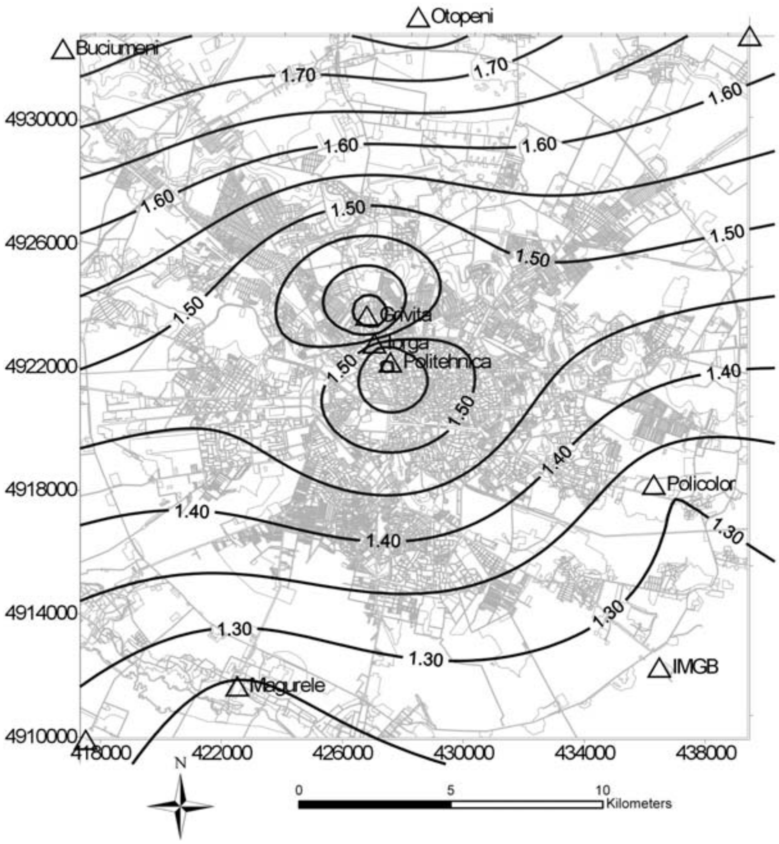

Fig. 3 – Map of the characteristic site period for the Bucharest City. Coordinates are given in UTM system [meters]. Borehole sites are represented by triangles.

The fundamental periods obtained with *Nakamura's method* by Zaharia et al., 2008 [13] are in good agreement with those computed on the basis of geological and geotechnical data presented by Bala et al., 2007c [14], which show an increase of the fundamental period in the Bucharest area from south to north, in the same direction as the increase of the thickness of the Quaternary deposits.

Similar results obtained by both methods lead to the conclusion that we should consider the bedrock in Bucharest as being the Fratesti layer (7-th sedimentary layer), with an average depth of 140–150 m and with a computed V_s mean value of 350–410 m/s for the package of sedimentary layers covering the bedrock layer (Bala et al., 2007c [14]).

Aldea et al., 2006 [8] reported a value of fundamental period of 1.54 s for the borehole of 140 m depth at NCSRR/INCERC. The average value of V_s computed for this borehole is 364 m/s, in good agreement with the results in the present paper.

3.2. MEAN WEIGHTED SEISMIC VELOCITY V_{S-30} AND V_{S-50} IN BUCHAREST CITY

Seismic velocities in the Table 1 are obtained by several authors by seismic measurements in boreholes in the period 2006–2007. They were gathered in order to compute the mean weighted seismic velocity for the first 30 m depth (V_{S-30}), for each case according to formula (1).

An improved map of V_{S-30} is presented in the Fig. 4. According to the map in Fig. 4 the V_{s-30} has a range from 220 to 320 m/s. The northern part of Bucharest is characterized by rather low velocity values, under 280 m/s, while in the south medium values are encountered. The central part is characterized by a low value zone around City Hall and Municipal Hospital, followed to the north by high values (Grivita) and to the east by medium values (UTCB Tei).

The V_{S-50} map shows a range of higher velocity values, from 270 to 340 m/s, with low values in the north, and medium to high values in the central part of the city (Fig. 5). A pronounced minimum is present in the center around the sites of City Hall and Municipal Hospital, both located near Dambovita river, with velocity values under 300 m/s. Three sites show high values of above 340 m/s (Grivita, Romanian Shooting Federation and Titan 2 Park).

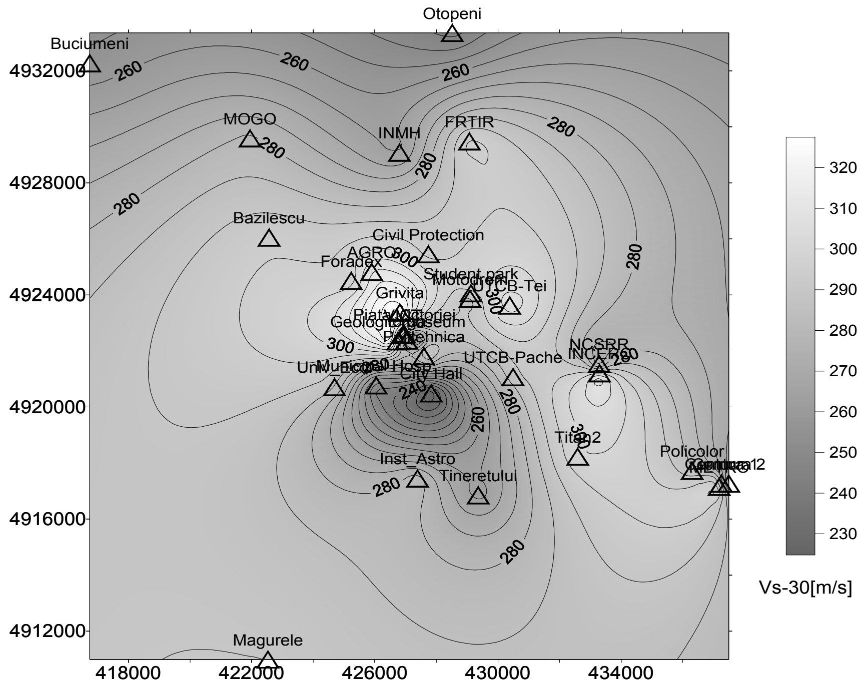

Fig. 4 – Map of the mean weighted seismic velocity (V_{S-30}) in Bucharest City from downhole seismic measurements. Coordinates are given in UTM system (meters).

Table 1

Mean weighted seismic velocity for the first 30 m depth ($V_{S\text{-}30}$) and 50 m ($V_{S\text{-}50}$) obtained in different sites in Bucharest City

No.	Borehole	$V_{S\text{-}30}$	$V_{S\text{-}50}$	References
1.	Grivita_110	**330.9**	**341**	Bala et al., 2006 [3], Bala et al., 2007b [4].
2.	Politehnica_200	**297.2**	**310**	
3.	Policolor_100	**286.0**	**292.5**	
4.	Otopeni_200	**243.1**	**274**	
5.	Magurele_112	**289.8**	**313**	
6.	Iorga_170	**245.1**	**254.6**	
7.	Foradex_81	**295.7**	**315.4**	
8.	Buciumeni_150	**255.8**	**281**	
9.	Bazilescu_172	**247.3**	**248.2**	
10.	Centura 1	**288**	**318.4**	
11.	Centura2	**260.5**	**292**	
12.	Tineretului Park	**263**	**304**	Bala et al., 2007a [9].
13.	Univ_Ecologica	**281**	**326**	
14.	Inst_Astronomic	**283**	**320**	
15.	Titan2 Park	**308**	**341**	
16.	Motodrom Park	**288**	**327**	Ritter et al., 2007 [10].
17.	Student Park	**295**	**319**	
18.	Romanian Shooting Fed.	**297**	**347**	
19.	Geologic Museum	**320**	**328**	
20.	AGRO	**311**	**--**	Hannich et al., 2006 [7].
21.	BAZI	**267**	**--**	
22.	INCERC	**311**	**--**	
23.	INMH	**264**	**--**	
24.	METRO	**303**	**--**	
25.	MOGO	**281**	**--**	
26.	VICT	**290**	**--**	
27.	City Hall	**219**	**258**	Aldea et al., 2006 [8].
28.	Municipal Hospital	**245**	**281**	
29.	NCSRR/ INCERC	**270**	**302**	
30.	Piata Victoriei	**284**	**310**	
31.	UTCB -Pache	**288**	**318**	
32.	Civil Protection	**293**	**309**	
33.	UTCB - Tei	**309**	**326**	

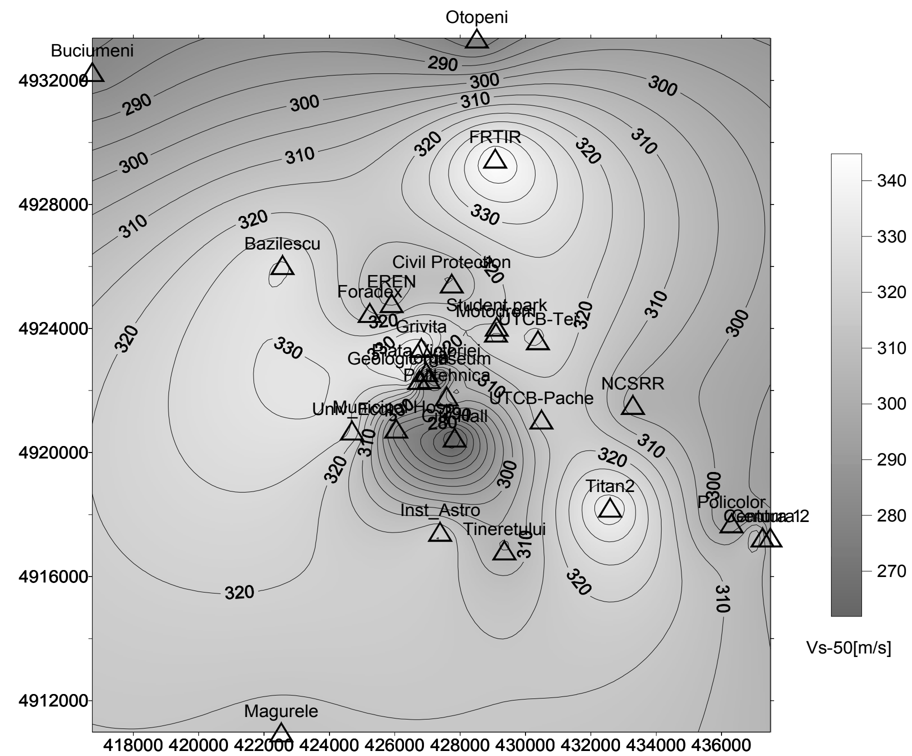

Fig. 5 – Map of the mean weighted seismic velocity ($V_{S\text{-}50}$) in Bucharest City from downhole seismic measurements. Coordinates are given in UTM system (meters).

4. CONCLUSIONS

1. The earthquake of 27.10.2004 was one of the most studied as there were many good recordings in the Bucharest City area. Based on the free field accelerometer network of National Institute for Earth Physics, the PGA map for Bucharest was computed for the 3 components. The horizontal EW component shows variation in the PGA with amplitudes ratio of 1/4 (16 to 60 cm/s^2) in the city area (Fig. 1). Most of this variation is due to the package of the Quaternary sedimentary layers which amplify the original strong motion arrived from the earthquake at the bedrock.

2. The Quaternary local geology in Bucharest City is rapidly changing from one point to another in only a few hundreds of meters (Bala et al., 2006 [3] and 2007b [4]). The geological layer which is considered the bedrock is the Fratesti layer A, with 100 m depth in the south and 200 m depth in the north.

The real succession of the 7 principal layers as well as their physical properties can be ascribed only by in situ measurements in boreholes.

3. The largest amplification of the soil will occur at the lowest natural frequency or its fundamental frequency. The period of vibration corresponding to the fundamental frequency is called the characteristic site period. The characteristic site period, which only depends on the soil thickness and average shear wave velocity of the soil, provides already a very useful indication of the period of vibration at which the most significant amplification can be expected. The map (Fig. 3) shows an increase in the characteristic site period, from 1.25 s in the south to 1.75 s in the north, due to the general increase of the depth to Fratesti Layer A from south to north. This result is in good agreement with previous investigations reported by Bonjer et al., 1999 [12]; Mandrescu et al., 2004 [11]; Bala et al., 2007b [14]; Zaharia et al., 2008 [13]. In the same time the results narrows the domain of the fundamental frequencies between 1.25–1.75 s.

Due to the different values of mean weighted velocity for each site, some variations appear right in the central part of Bucharest, which is the most sensible zone vulnerable to strong seismic events. In several particular sites, the values of the characteristic site period have almost the same values as those computed in the same sites using an entirely different method: the spectral ratio H/V method applied to seismic noise measurements (Bala et al., 2007c [14]; Zaharia et al., 2008 [13]).

In the future editions of the earthquake resistant design code, the ground categories should also include the predominant period of the site and not only the characteristics of the upper 30 m of the geologic profile, since the important thickness of the sediments above the bedrock layer (100 m – 200 m in Bucharest), as well as their properties can induce long periods with spectral amplification over 1 s.

4. The amplification of PGA due to the top 30 m of the soil profile was proved to have the major contribution for the surface ground motion PGA. The same aspect was observed for the acceleration response spectra: the spectra at surface are amplified in respect with the spectra in boreholes by a factor of 2–3 (Bala et al., 2006 [3], Aldea et al., 2006 [8]).

Seismic velocities in the Table 1 are obtained by several authors by direct seismic measurements in boreholes. They were gathered in order to compute the mean weighted seismic velocity for the first 30 m depth (V_S-30) and 50 m depth (V_S-50), for each case, according to formula cited in the Romanian Code for the seismic design for buildings - P100 -1/2006 [5] and in EUROCODE 8 [6].

All the $V_{S\text{-}30}$ values in Table 1 belong to type C of soil after this classification (Romanian Code for the seismic design for buildings - P100-1/2006). Even the $V_{S\text{-}50}$ values in the Table 1 fall in the type C of the classification (180 m/s < $\bar{V}_S$ < 360 m/s). According to this code, the elastic response spectra characterizing the 4 classes of the soil conditions will be determined using the methodologies in the international practice.

5. A map with V_{S-30} distribution is presented in the Figure 4 for the Bucharest City area. According to this map, the northern part of Bucharest is characterized by rather low velocity values, while in the south-west medium values are encountered. The central part is characterized by a complex mixture of low values (Iorga_170) with medium (Politehnica_200) and high values (Grivita_110). The V_{S-50} map shows almost the same range of the velocity values from 270–340 m/s, with low values in the north, and medium to high values in the central part of the city (Fig. 5). This image shows that in the central part of the Bucharest, where low value areas are mixed with high values, new seismic measurements are needed in order to have an improved image of this important parameter which has a great impact on the microzonation map of the Bucharest City, Romania.

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