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Ground motion amplifications for Bucharest based on 3D geological model and assigned geophysical properties

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Abstract

The evaluation of seismic hazard at local scale, with the contribution of strong-motion data from a dense seismic network and insightful geological and geophysical data, is one of the key components in seismic risk mitigation. Significant efforts were made to record and predict the highly variable peak spectral amplification values of strong seismic motion in Bucharest, capital city of Romania, especially after the 4 March 1977 Vrancea earthquake with a moment-magnitude of 7.4, which resulted in 1424 victims in the city (90% out of the national casualties).

Using a recently compiled geological database, which relies mostly on several hundreds of borehole measurements performed for the subway in Bucharest and a recent DEM for the area, this study establishes the positions of the main seven Quaternary layers beneath the city.

In this paper we review studies referring to shear wave velocity (V_S) measurements in the area of Bucharest – as key input for seismic site amplification models and microzonation maps, selecting and reprocessing some data in order to obtain a homogenized database. This contains mean weighted V_S values for the uppermost 30 m, 50 m, 70 m and 100 m depth intervals.

By mapping and interpreting the newly assembled geological model, as well as the assigned geophysical values (shearwave velocity), we begin to compute the spectral amplification values at surface, using the data recorded at the earthquake from 27.10.2004 at surface and in the depth.

The spectral modelling is applied to deeper models than the uppermost 30 m, and considering the 50 m, 70 m and 100 m depth intervals, where we have now an important database for weighted mean shearwave velocities (V_S) in the depth. The results attested the importance of this action and we present solid results that the values computed for the deeper models are closer to the computed surface values, especially for the depth intervals of 70 and 100 m depth.

The spectral acceleration values as well as the PGA computed at surface are based first on new database of geological model and assigned geological emerging in the last years, as well as on an extended measuring of the strong motion values of an earthquake at surface and also in the depth down to 100 m depth.

Keywords: Shear-wave velocity; Site amplification; Microzonation; Seismic hazard; Bucharest city

1. Introduction

In local seismic hazard (microzonation) studies, the availability of accurate local determination of the shallow soil layers characteristics are determinant in order to determine the local response under various seismic scenarios. The results of 2D and 3D modelling can reflect the local variability of the soil package, leading to the understanding of potential building damage and measures of seismic risk mitigation. In large cities located on thick layers of sediments (such as Bucharest – capital city of Romania), affected also by earthquakes with variable source parameters, detailed input data regarding geological and geophysical data but also real strong motion recordings (at surface and in boreholes) are important for determining relevant building design parameters. In situ measurements of shear wave velocity (V_S) and soil thickness provide a direct measure of the characteristic site period. Seismic noise measurements are an accessible method and computed H/V spectral ratio can also provide a good indication on the fundamental frequency of the site. New seismic methods for measuring and determining V_S have been derived and employed in the field in Bucharest in recent years.

The city area of Bucharest presents geological conditions which, in the context of strong motion induced by intermediate-depth earthquakes in the Vrancea seismic zone, occurring in a restricted area in Southern Carpathians Arc zone located at 130-190 km hypocentral distance NE from the city, are contributing to high level site effects spread all over the city area. Local geological conditions lead to significant local site amplification and variability of parameters at surface and as such different damage distributions are occurring in the case of a strong earthquake from the Vrancea zone (Toma-Danila and Armas, 2017). Among the key geological features present in Bucharest underground, there are:

- an alternation up to 150-200 m of thick Quaternary sand, pebbles and clay and marl layers near surface;
- strong lateral heterogeneities and important vertical thickness variations of soft soil deposits and three; three main aquifers, complicating the geologic structure in the first 100-150 m depth;
- three main porous aquifer systems among the sand and clay layers, some of them are interconnected;
- the absence of hard bedrock in the first 100-150 m depth, the first geological limit with such characteristics occurring at Cretaceous upper limit (K3), at 500 m depth in the south of Bucharest, and reaching 1500 m depth in the north part of the city (Lacatusu et al., 2007; Bala et al., 2010).

2. 3D digital geologic model of the 7 principal Quaternary complexes

2.1 General classification Quaternary deposits in Bucharest area

A first classification on the geological and lithological description of the Quaternary deposits in the Bucharest area was made by Liteanu (1952), which was first accepted, in the beginning of XXI century, by the researchers for beginning studies about the site effects and microzonation of Bucharest (Lungu et al., 1999; Bala et al., 2005; Mandrescu et al., 2004).

This classification of 7 main layers (geological complexes beginning from the surface to depth) is and improved through the works of Ciugudean-Toma et al. (2004) on hundreds of boreholes performed by METROUL S.A. on the principal subway lines from Bucharest underground.

The distribution of these geologic complexes in the depth across Bucharest ring zone, as well as their principal geotechnical characteristics of each layer complex are published by Ciugudean-Toma and Stefanescu (2006), based on the geological data, as well as probes from several hundreds of boreholes.

The classification was generally accepted in the beginning of XXI century by all researchers in their studies about dynamic properties of the sedimentary layers in and around Bucharest City (Hannich et al., 2006; Kienzle et al., 2006; Marmureanu et al., 2010; Bala et al., 2011; Bala et al., 2014; Manea et al., 2016). By adopting and working with the same classification of shallow sedimentary layers, the cited researchers make their respective results more prone to be directly compared and analogies of the results to be established.

The classification of the 7 principal layers (geologic complexes) with general characteristics after Ciugudean and Ștefanescu (2006) comprises the following main layers (or complex sedimentary packages).

- **Layer 1:** ***Anthropogenic backfill and soil***, with a thickness varying between 3-10 m
- **Layer 2**: ***Upper clayey-sandy complex*** representing Holocene deposits of loess, sandy clays and sands; the thickness of this complex varies between 2 and 5 m in the inter-fluvial domain, 10-16 m in the northern and

southern plain and 3-6 m in the river meadows

- **Layer 3:** ***Colentina gravel complex***, bearing the Colentina aquifer, is a layer containing gravels and sands with varying grain size distribution
- **Layer 4:** ***Intermediate clay layer*** contains up to 80% hard consolidated clay and calcareous concretions with intercalated thin sand and silt lenses; this layer is not always present (see Fig. 1) and varies from 1-25 m thikness.
- **Layer 5:** ***Mostistea sandbank***, bearing the Mostistea aquifer, is a sand layer with sands of medium to fine grain size. The thickness varies in the area of Bucharest between 1 and 25 m.
- **Layer 6:** ***Lacustrine complex*** (or Lagoon complex) is composed by a variation of limy-marled clay and fine sands, the grain size <0,005 mm consisting about 86%. The thickness varies from about 60 m in the southern part of Bucharest to about 130 m in the North. The variable thickness is due to the underlying Fratesti complex which descends northward.

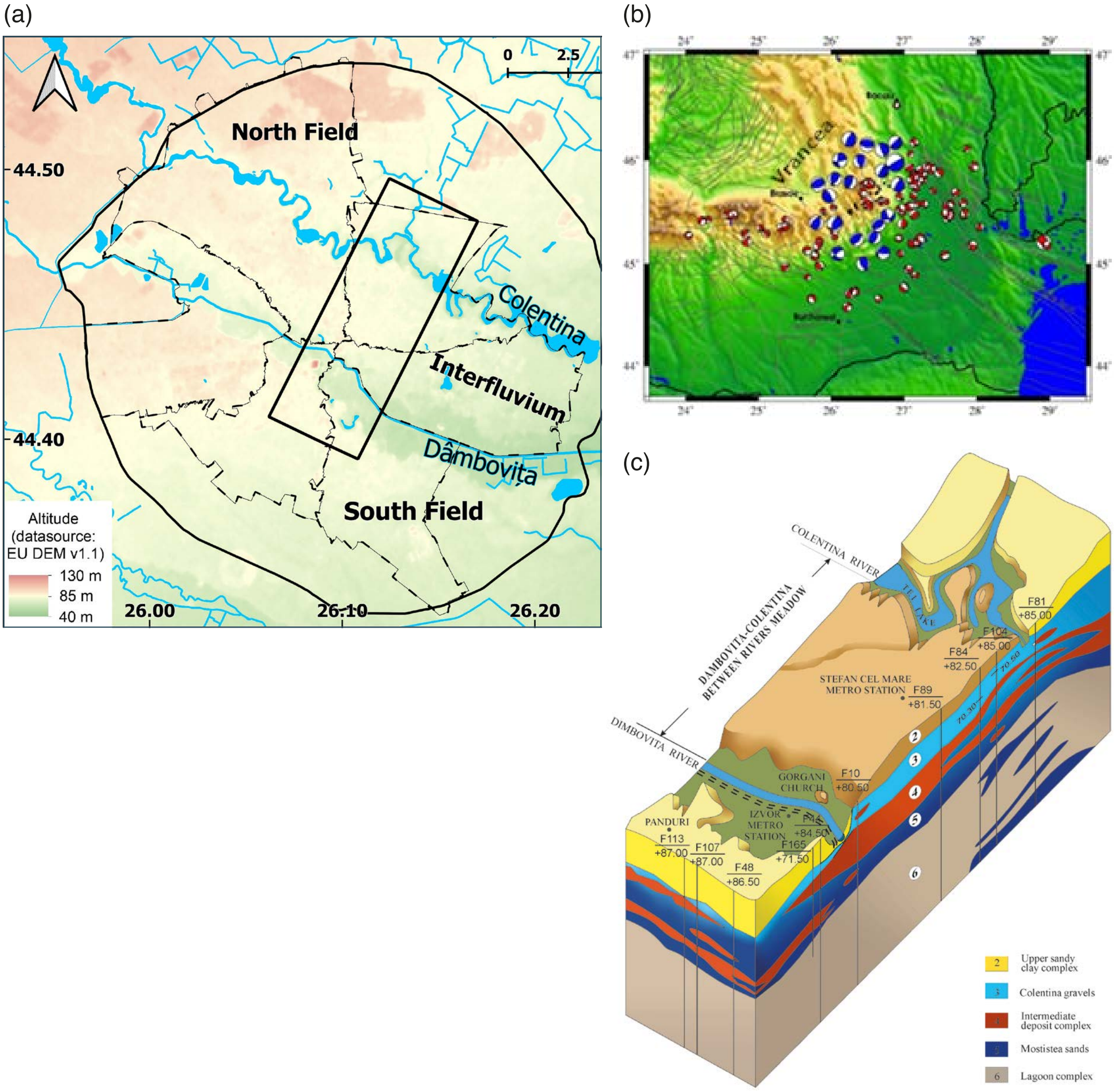

Figure 1. (a) Topographic map of Bucharest (datasource: EU-DEM version 1.1.) with the placement of the block in 1c. (b) In the inset the focal mechanisms for 60 crustal earthquakes (red circles) and 22 intermediate depth earthquakes with Mw > 4.5 (blue circles) from Vrancea intermediate-depth zone (VNI) are represented. (c) Schematic geomorphological section of Bucharest undergound, with principal sedimentary layers 2-6 after the work Ciugudean et al. (2004), depth scale is exaggerated. The section is modified after Ciugudean-Toma and Stefanescu (2004).

- **Layer 7:** ***Fratesti complex***, bearing the Fratesti aquifer, lies discordant on Pliocene Levantine clay layers. This complex comprehends three thick (10-40 m each) sandy gravel layers (named A, B and C), separated by two marl or clay layers (each of 5-40 m thickness). This thick complex (total thickness 100-180 m), with a continuous present in the whole area of Bucharest, dips northward; its upper surface lays at about 75 m depth in the southern part of Bucharest and at about 190 m depth in the North.

A more detailed description of the geotechnical characteristics of each layer is given also by Ciugudean-Toma and Stefanescu (2006), which analyse probes from boreholes, presenting the main characteristics of the layers in the depth, in points distributed over the city (some 10 geological boreholes are presented in Fig. 1c).

2.2 Database of the 7 principal Quaternary complexes underneath Bucharest

In the process of defining the shallow sedimentary layers in Bucharest, the geologists and geophysicists obtained results in the field that proved great differences in the geometry of the layers succession and also great lateral heterogeneities in respect to lithology, thickness and physical properties almost in each part of the Bucharest city.

The first step in the generation of the digital geological model (DGM) was the acquisition and the digital processing of pre-existing geological and geotechnical data. These data consisted of analogue maps at various scales that displayed the location of the drillings, geological cross sections and borehole logs. The primary data provider was S.C. METROUL S.A., Romanian subway construction company, which was involved in performing the geological and hydrogeological boreholes on the main underground lines in Bucharest, beginning with the 1980's. In our DGM we include data from other projects, see for example Bala et al. 2010 for the 10 drillings in Fig. 2.

The maximum depth for the 10 drillings was 50 m, which has proved to be not enough for modeling purposes in the shallow geologic environment of Bucharest city. Deeper geologic models should be considered in this particular case, which would increase considerably the cost of the research. The depth of the drillings being limited to 50 m in each case, they did not intercept the engineering bedrock, considered at that time to be at the Fratesti A stratum (100-150 m depth, after Mandrescu et al. 2004).

According to some other studies this layer cannot be considered as engineering bedrock, because it is a principal aquifer, which has none of the principal geotechnical characteristics of a bedrock (Bala et al., 2011; Bala, 2014). According to these sources, the bedrock might be considered lower than 200 m depth, interval for which we have only a few direct measurements, or even at the geophysical interface between Tertiary and Cretacic, where a jump of the values of V_S seismic velocities is well documented during Vrancea'99 refraction experiment by Raileanu et al. 2005.

This hypothesis is confirmed also by Sebe et al. 2009, which is using the dispersion of Love waves, and infer one model of shear-wave velocity structure underneath Bucharest city in which this interface is having a slope from 500 m in the south of Bucharest, down to more than 1500 m in the north part of the city, that can contribute essentially to seismic hazard estimation in the zone.

The last geologic and geophysical model is confirmed by Manea et al. 2016 in their study about the shear wave velocity structure beneath Bucharest (Romania) using surface waves recordings generated by ambient vibrations.

2.3 3D digital geologic model underneath Bucharest city

Eventually, data comprising of point coordinates, depth at the 7 main Quaternary complexes beneath Bucharest and layer thickness were included in a GIS database, along with surface elevation determined based on the European Digital Elevation Model (EU-DEM), version 1.1 and a database with geological model of Bucharest have emerged (Toma-Dănilă et al., 2025) in the Fig. 3. In total, we gather the data from an amount of:

- 969 boreholes for layer 1;
- 349 boreholes for layer 2;
- 340 boreholes for layer 3;
- 331 boreholes for layer 4;
- 274 boreholes for layer 5;
- 59 boreholes for layer 6;
- 47 boreholes for layer 7.

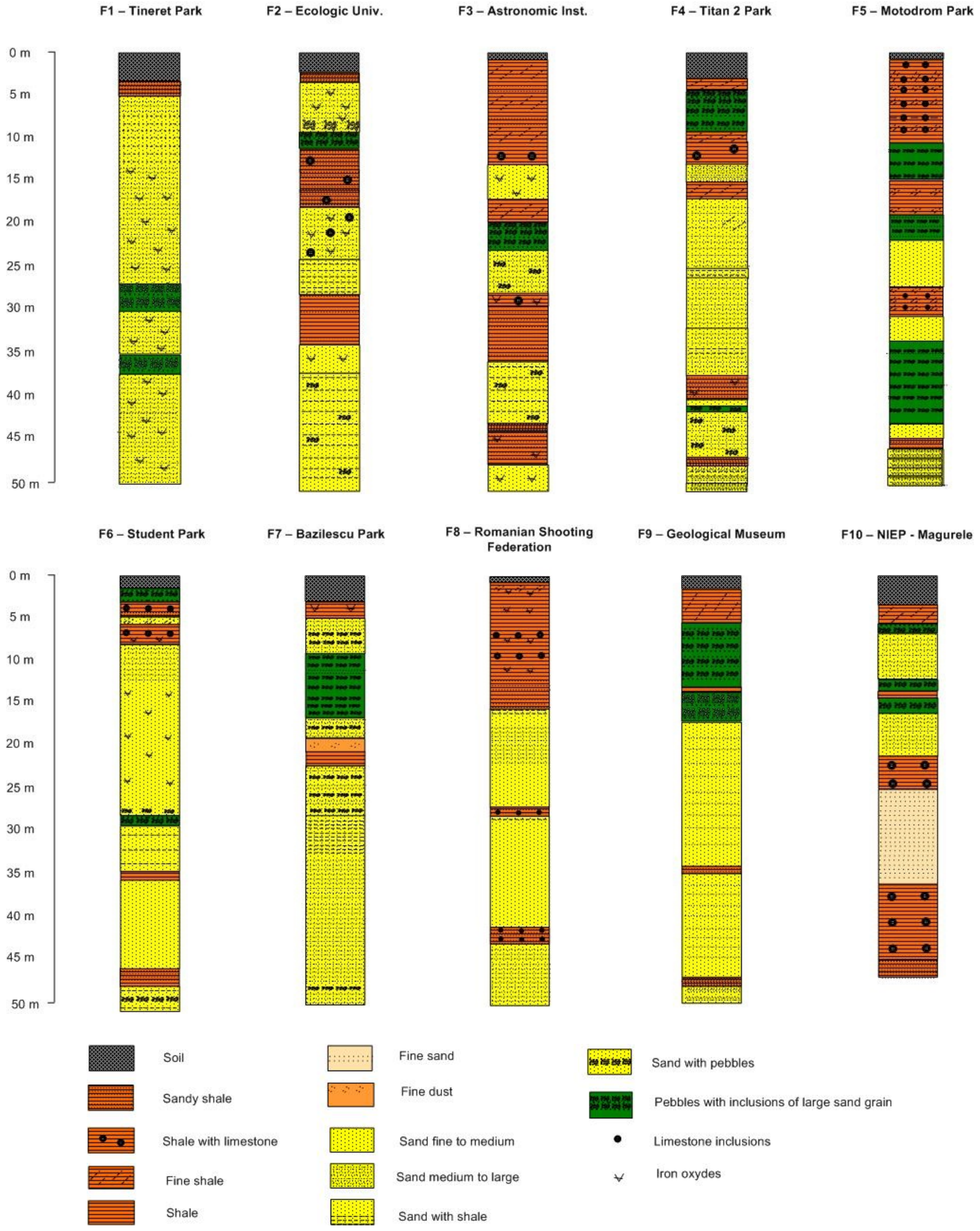

Figure 2. Lithological columns determined in the ten boreholes investigated during the NATO SfP project 981882. Numbers correspond to the main Quaternary layers/complexes as given before. These complexes may comprise several sub-layers. Their positions are given in Fig. 5 (after Bala et al., 2010).

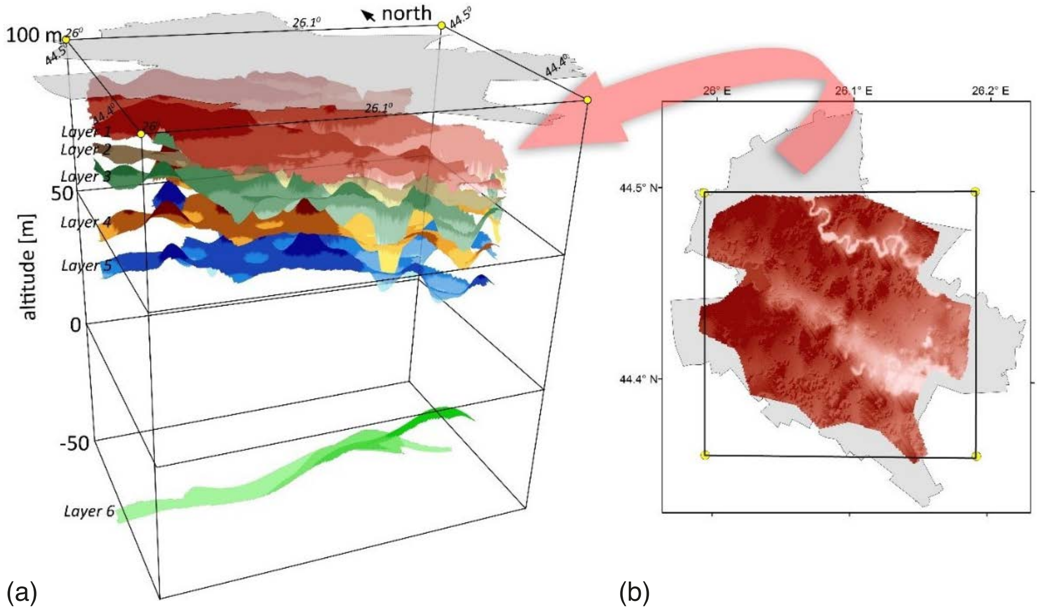

Figure 3. (a) 3d representation of the Digital Geological Model (DGM) for Bucharest (after Bala et al., 2023a). (b) Representation of the base of first layer placed on the Bucharest map.

The last 3D model is based on the raw data (geologic columns) from hundreds of drillings in Bucharest, provided by METROUL S.A., which were not published until now. A composite 3D geologic model of the city is represented in Fig. 3 in the frame of this database and also based on the topographic reference the EU-DEM version 1.1.

In the 3D geologic model the position and depth of the principal 7 sedimentary layers are presented across the city, together with the thickness of each layer. Using the GIS program, one can find out the data values in any point of a regular network constructed over the city. They are also representing the base input data used by geophysicists in order to place the mean weighted values of V_S and to determine the spectral amplification of the seismic signal, from a depth of 70 m to the surface, which can be calibrated with the spectral amplification of a real seismic record at surface (Bala et al., 2023).

The description of this 3D model, the sources employed, as well as the main applications can be found in Bala et al. 2023, which was based on the complete geological database published and maintained by Toma et al. 2025.

3. Shear-wave velocity values (V_S) assigned to shallow soil types in Bucharest city

Mean weighted shear-wave velocity in uppermost 30 m depth interval ($\overline{\mathbf{V}}_{\mathbf{S30}}$) is considered by Eurocode 8 (European Committee for Standardization, 2004) and the Romanian Seismic Design Code P100-1/2013 (UTCB, 2013) to be usually a useful indicator in seismic hazard assessment – revealing areas with generic variations of average seismic velocities. However, for seismic site amplification models and nonlinear site response analyses in areas with thick layers of sediments such as most major cities, $\overline{\mathbf{V}}_{\mathbf{S30}}$ might not reflect adequately the soil characteristics leading to significant amplification variabilities (Marmureanu et al., 2016).

Several studies, among which Von Steht et al. 2008; Bala et al. 2014, have emphasized that V_S is important to be known until deeper depths (of 100-150 m for example) for Bucharest. These values are one of the key input data to algorithms which estimate the spectral acceleration response and transfer functions for every site in which in situ measurements are performed (such as SHAKE). As such, in this study we review many recent studies presenting measured V_S values (by different methods) in the Bucharest area and select representative values in order to obtain a homogenized database of mean weighted V_S values at 30, 50, 70 and 100 m. Elevation of terrain is extracted from the Digital Elevation Model (DEM) EU-DEM versions 1.1. 3D Maps revealing a broader zone than previous studies (such as Kienzle et al., 2006) characterized by a complete collection of V_S values, which are generated and evaluated.

3.1 Seismic codes and V_S velocity values asigned for several soil types

For the study of site effects in Bucharest, the necessity to acquire more reliable V_S values for shallow Quaternary layers is a task with the aim to improve the city microzonation.

For standardisation purposes, the Romanian Seismic Design Code (UTCB 2013) recommended that mean weighted values for V_S are computed for each site (borehole), using the following formula:

$$\bar{V}_S = \frac{\sum_{i=1}^{n} h_i}{\sum_{i=1}^{n} \frac{h_i}{V_{Si}}} \tag{1}$$

where h_i (m) and V_S (m/s) denote the thickness (in meters) and the shear-wave velocity $\bar{\mathbf{V}}\mathbf{s}$ (m/s) of the *i-th* layer, in a total of *n* layers, existing in the same type of stratum, as they are described in Romanian Seismic Design Code P100-1/2013 (UTCB, 2013) and EUROCODE 8.

In Eq. (1), 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, found in the same type of stratum. According to the same design code, for $\bar{V}_{S30}$, 4 classes of the soil conditions are defined:

- Class A (rock type): $\bar{V}_S > 760$ m/s;
- Class B (hard soil): $360 < \bar{V}_S < 760$ m/s;
- Class C (intermediate soil): $180 < \bar{V}_S < 360$ m/s;
- Class D (soft soil): $\bar{V}_S < 180$ m/s.

All the $\bar{V}_{S30}$ values in Table 2 belong to type C of soil after this classification. In Eurocode 8 (European Committee for Standardization, 2004), the values for class A (rock type) are >800 m/s.

Another critical value in site effects is to estimate characteristic period of the site, defined as period of vibration corresponding to the package of layers from a certain depth to the surface. The vibration period of soil layers is depending the depth and also on the mean weighted velocity computed with Eq. (1) for that depth and is calculated using Eq. (2) in UTCB (2013):

$$T_S = \frac{4h}{\bar{V}_S} \tag{2}$$

The characteristic natural period of a specific site (down to a certain depth) has to be considered in relation with vibration period of structure in order to estimate the amplification effects that might occur at the coupling of soft soils/building – resonance. In their study, Aldea et al. (2007) considered values of characteristic periods between 0.7-1.53 Hz at 7 sites, according to the depth of the boreholes and velocities in Table 1 (column 7).

The V_S values obtained by different methods and within several research projects for Bucharest (Bala et al., 2011) were used to determine $\bar{V}_S$ by using Eq. (1) (columns 3, 5, 7 had to be recomputed from original data). $\bar{V}_S$ values are presented in Table 1, for each of the seven Quaternary layers in Bucharest, having different thickness.

The $\bar{V}_S$ values obtained using different methods such as in boreholes, by penetration tests SCPT or at the surface in Bucharest (seismic refraction) are generally very close.

The average densities presented in Table 1 are actual densities determined after laboratory measurements in the NATO SfP Project 981882 – the experiment including core sampling of the representative sedimentary layers and determining the geotechnical values for each layer under laboratory conditions (Arion and Neagu, 2006; Bala et al., 2013).

Because the shallow Quaternary layers in Bucharest present relative great laterally changes in thickness and also in lithology, the only way to get reliable geotechnical and seismic velocity data may be guaranteed by in situ measurements in boreholes or by special methods on the surface. In order to use the values presented in Table 1 for modelling of acceleration response spectra in random points of the Bucharest map, one need to know the 3D exact position of the seven complexes in the underground of Bucharest area.

Table 1. Comparison of $\overline{\mathbf{V}}_S$ weighted values [m/s] obtained from different research projects and methods for the Quaternary layers in Bucharest between 2002-2009 (modified after Bala et al., 2011).

Number and name of the Quaternary layer	Densit. [g/cm^3]	MOVSP (7-sites) $\overline{V}_S$ [m/s]	Down-hole (12 sites) $\overline{V}_S$ [m/s]	SCPT (10 sites) $\overline{V}_S$ [m/s]	Down-hole (10 sites) $\overline{V}_S$ [m/s]	Boreholes UTCB/NCSRR (7 sites) $\overline{V}_S$ [m/s]	Refraction profiles		Mean value Colums 3 – 8 / std. [m/s]
							V_s site A [m/s]	V_s site B [m/s]	
1. Backfill	1.75	–	167	–	169	195	140-175	175-195	175.2 ±8.19
2. Upper clay layer	1.96	262	223	262	252	265	275-280	230	253.4 ±7.99
3. Colentina layer	2.05	340	254	267	320	327	315-350	300-345	308.3 ±8.19
4. Intermediate Clay layer	2.02	391	319	296	367	364	–	365	350.3 ±8.19
5. Mostistea sandbank	2.05	392	350	322	386	405	–	–	371 ±9.2
6. Lacustrine layer	2.14	429	405	–	417	–	–	–	417 ±2.8
7. Fratesti layer (A)	2.05	511	544	–	–	–	–	–	527.5 ±4.4

3.2 Review of the methods and results of shear-wave velocity measurements performed in Bucharest

The initiation of in situ geophysical activities aiming at obtaining seismic velocity recordings (V_S and VP) begun around the year 2000 when Romania was host of a great cooperation involving specialists from Germany working along with Romanian specialists. In order to study this seismically high-risk area a joint German-Romanian research program was initiated by the Collaborative Research Center 461 (CRC 461) "Strong Earthquakes – a Challenge for Geosciences and Civil Engineering" at the University of Karlsruhe (KIT, Germany) and the Romanian Group for Vrancea Strong Earthquakes (RGVE) at the Romanian Academy in Bucharest (Wenzel, 1997).

The measurements of the in situ seismic velocities were performed and reported in the frame of this German-Romanian Program; Hannich et al. 2004; 2006; Lungu et al. 2005; Bala et al. 2005; 2006; 2010; Aldea et al. 2006.

A report about all these activities is given by Bala et al. 2011, from which we can choose and present the results of recorded seismic velocities in Table 1. The results are given in mean weighted values for V_S are computed for each site in Bucharest area and also for each of the 7 principal geological layers in the underground.

The mean V_S values computed for each seismic layer, as well as the standard deviation for the values assigned to each layer are given in the last column. The results can be considered very close because we have a standard deviation between 4,4 and 10% for all the measurements made by some 7 different teams, which were employing 6 different methods of measuring in situ seismic velocities.

After that the work continue in the frame of NATO SfP project 981882, also a German-Romanian cooperation, in which 10 new boreholes were drilled in central Bucharest area, down to 50 m depth. During drillings they were probed for samples of sedimentary layers and, after they reached 50 m, the drillings were cased and measured for seismic wave velocities VP and V_S. The results are presented in Table 2 and we can see that the weighted velocity values (V_S) are very similar with those in Table 1.

Surface waves derived methods as MASW

Surface-waves (Rayleigh wave) consist in elastic waves propagating along the ground surface and its energy concentrates near the ground surface. The surface-wave velocity of propagation strongly depends on S-wave velocity until 25-30 m depth. The surface wave method is the seismic exploration method in which the dispersion character of the surface-waves is analysed.

The seismic velocity is usually measured by down hole measurements, but later the new methods MASW (Multichannel Analysis of Surface Waves) method are employed to obtain V_S values in the first 25-30 m from surface The surface waves method is a passive seismic exploration method in which the dispersion character of the surface-waves is analyzed and V_S can be obtained only in the first 25-30 m depth. The surface-wave method can be used successfully in the environment of a big city, without the need of drilling a borehole, which makes the method a comparatively cheap one.

Arion et al. (2012) are applying the surface waves method near the site at UTCB – Tei and presented the results. However, the example presented of a MASW measurement at UTCB site show V_S between 150 m/s at surface and 210 m/s (at 20 m depth). These are rather low values compared with $V_{S\text{-}30\mathrm{m}} = 309$ m/s, determined for the same site from previous classic down-hole seismic measurements (Aldea et al., 2006).

For 7 sites where ground survey was conducted by both seismic downhole (Arion et al., 2012) and MASW methods, a comparative analysis of V_S, values corresponding to each depth interval in soil profile and VS30 has been performed by Calarașu et al. (2018). VS30 data obtained from MASW are ranging from 189 m/s to 302 m/s, while the values obtained by downhole are in the range 263-309 m/s. Differences between VS30 values obtained during downhole and MASW surveys are ranging from 15-35%, probably due to constrains of depth investigation limitation, sensors sensitivity, procedure and equipment specificity and great lateral discontinuities of soil profile.

For both examples presented here we have chosen the values obtained by downhole to be included in our database, although all the examples can be included in soil class C.

In recent years the activity of measuring in situ seismic velocities was not continued, due to multiple factors. A recent example is presented by Pavel et al. 2021. The author is reporting some 42 boreholes from which he extracted the data and and he presented in the upper 50 m of soil. He reported some variability of the shearwave velocities from 275 m/s (10 m) to 355 m/s (30 m) and 389 m (50 m). The author did not offer a table with the cited boreholes, but in our sources the V_S is almost 100 m/s lower for each of the case in several hundreds of boreholes in Bucharest.

Further in the cited paper, the authors claimed that they found ‚mean shearwave velocity' of 285 m/s (30 m) and 314 m/s (50 m depth), without pointing out where they found these values.

In all our paper we are using weighted seismic velocity V_S, computed with Eq. (1), as it is required also in Romanian Seismic Design Code P100-1/2013 (UTCB, 2013).

However, comparing these values (Pavel et al., 2021) with our weighted shearwave velocities in Table 2, we have found a good match, with a minor difference of about 10-12 m/s in both cases.

We also have to mention that it is no reference to the geology in all the article, except for the term ‚soil' (Pavel, 2021). On the contrary in our sources the geology in the undergorund of Bucharest is very important, because in this way, we are ‚exporting the properties' and assign the same properties that we have measured in some boreholes, to other points in the city, where we can find the same layer succession in the depth in a geological drilling.

We have to mention that for all the sources mentioned in Pavel F. 2021 paper for these boreholes, the respective sources are introduced in our database, except that of Calarasu et al. 2016.

3.3 V_S database for Bucharest City area

To overcome the problem of heterogeneities of thickness and lithology, providing homogenized input for seismic site amplification models, integrative $\overline{V}_S$ values applicable throughout the whole city area of Bucharest were deduced for four fixed depths (30 m; 50 m; 70 m; 100 m), with no link to the 7 layers earlier presented. V_S values obtained by different methods and authors are used in this database and weighted using Eq. (1). Final results are organized in a spreadsheet table, which mentions the original data references (shown also in Table 2 from Bala et al., 2021) and also provides interactive mapping, through Microsoft Excel's 3D maps module. In this database measurements data from the following boreholes are included:

- 55 points (drillings and SCPT locations) with $\overline{\mathbf{V}}_{\mathbf{S30}}$ values;
- 48 points (boreholes) for $\overline{\mathbf{V}}_{\mathbf{S50}}$ values;

- 21 points (boreholes) with $\overline{\mathbf{V}}_{\mathbf{S70}}$ values;
- 15 sites (boreholes) with $\overline{\mathbf{V}}_{\mathbf{S100}}$ values.

3.4 Maps of the mean weighted shear-wave velocity $\overline{V}_S$

From Table 2 in the database (Bala et al., 2021), we have used some SCPT measurements to complete the previous MOVSP measurements in places where they overlap. In other sites there were also several measurements performed in the same boreholes; for the INCERC test site we have considered only the last performed measurements presented by Aldea et al. (2006) and Aldea et al. (2007) at INC site and the 2 measurements presented by Hannich et al. (2014) for INCERC1 and INCERC2 sites. Sites 41-45 in Table 2 (in the database of Bala et al., 2021) represent short refraction lines (up to 300 m), located in 2 parks in Bucharest: Tineretului park (3 lines) and Bazilescu park (2 lines). They are documented in Von Steht et al. (2008) which give us the velocities from Table 1 (refraction profiles). However, the velocity values for these sites were not considered for our $\overline{\mathrm{V}}_{\mathrm{S}}$ maps, given the method limitations and multiple values per profiles, but only for validation and discussions.

In order to show an estimate of the expected $\overline{\mathrm{V}}_{\mathrm{S}}$ distribution throughout the city, two different sets of maps were created, based on our database, by using two different interpolation methods; 1) The kriging method; 2) The Inverse-Distance Weight (IDW) interpolation method. Both methods are presented in Bala et al. (2021).

Here we are presenting only the maps made with the Inverse-Distance Weight (IDW) interpolation method. Database values were used to generate (through interpolation), maps of $\overline{\mathrm{V}}_{\mathrm{S}}$ at 4 depth intervals, from the surface: 30 m, 50 m, 70 m and 100 m (Fig. 4).

3.5 V_{S} map interpretation and discussion about distribution of the values

The observation that the SHAKE types algorithms can provide a better fit between the predicted models of the spectral acceleration response and real recordings at surface if the depth of models is placed at deeper interfaces (Bala et al., 2014) leads to the need for deeper models of the V_S structure in the Bucharest area.

Most of the measurement sites are concentrated in the centre of the city, in the region that is the Interfluvium between Dâmbovița River and Colentina river. To the north and to the south there are less points, but enough to give a broad image of the V_S characteristics. The sites with low $\overline{\mathrm{V}}_{\mathrm{S}}$ values (220-260 m/s) are concentrated to the north-west, beginning with the first map (Fig. 4a-b), while relatively high values are occurring to the west and south parts, if we consider deeper depth down to 70-100 m (Fig. 4c-d). Only in Fig. 3d there are $\overline{\mathrm{V}}_{\mathrm{S}}$ values greater than 360 m/s.

The red crosses are marking the two place (Tineretului Park – TIN) and Bazilescu Park – BAZ) in which several refraction lines were performed and the values for the $\overline{\mathrm{V}}_{\mathrm{S}}$ on these lines, for the 30 and 50 m depth intervals. Their values are matching the values of the map in the surrounding areas, so they can be considered good checking points for the reliability of the maps.

In the interpretation of the results, some other factors as geomorphological, geological and hydrogeological variations throughout the city need to be taken into consideration. As a trend, Fig. 3d shows a similar pattern with the topographic map in Fig. 1; lower $\overline{\mathrm{V}}_{\mathrm{S}}$ values correspond to the higher region of the city of 100-130 m altitude, while upper $\overline{\mathrm{V}}_{\mathrm{S}}$ values are distributed toward the south-east part, corresponding to lower region of the city (40-80 m altitude). For the south-eastern part of the city, due to the lack of measurement points (see also Fig. 4), we can appreciate the seismic velocities only from the values obtained at NIEP site (in Fig. 5).

The complete presentation of origin and content of the database, as well as the information about the geological database can be found at Bala et al. (2021). The set of maps that are constructed, as well as the distribution of V_S velocity in surface and in depth in Bucharest underground is accomplished, as well as an extensive discussion is presented by Bala et al. (2023).

In the model of V_S velocities In Bucharest IDW and kriging interpolation performed using ESRI ArcMap version 10.6 with the geostatistical and spatial analyst toolboxes (Bala et al., 2021). The degree of complexity of each method is different, but in conjunction they can show if a trend maintains or not. IDW assumes that each input point has a local influence that diminishes with distance and is able to keep values of observation in the specific points (but not exceed the minimum and maximum input values).

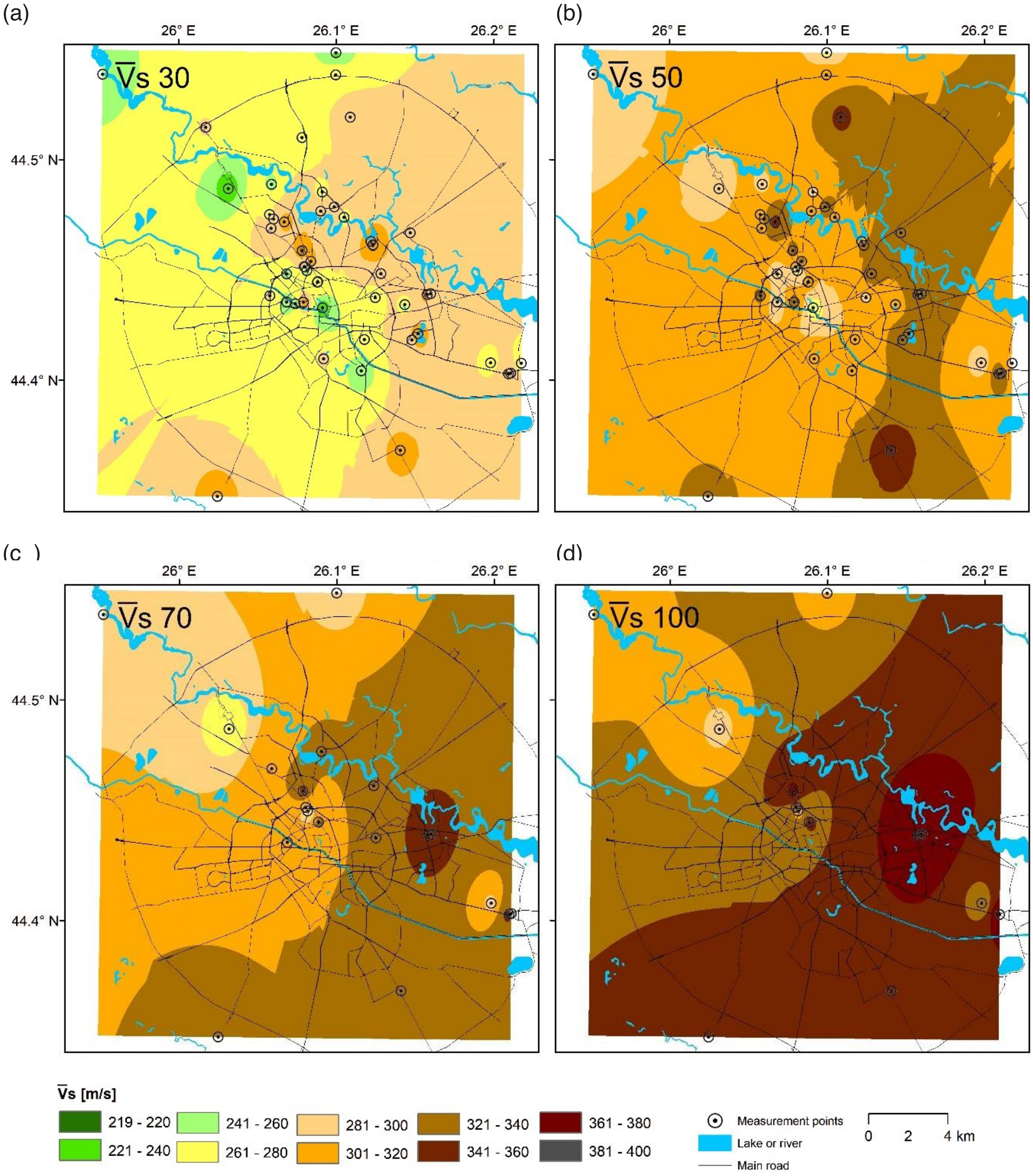

Figure 4. Maps showing the result of IDW interpolation of the $\overline{V}_S$ values at some of the sites considered for Bucharest, considering 4 depth intervals: (a) 30 m; (b) 50 m; (c) 70 m; (d) 100 m. Modified after Bala et al., 2022, oral presentation at 3ECEES in Bucharest, 2022.

4. Testing and calibrating response spectra with real ground motion models

Different methods of ground response analysis have been developed including one dimensional, two dimensional, and three dimensional approaches. Various modelling techniques like the finite element method were implemented for linear and non-linear analysis. Extended information on these analyses is given in Kramer (1996). Here we apply an equivalent linear one-dimensional analysis, as implemented in the computer program SHAKE2000 (Ordónez, 2012). The static soil properties required in the 1D ground response analysis with SHAKE2000 are: maximum shear wave velocity or maximum shear strength and unit weight. Since the analysis accounts for the non-linear behaviour of the soils using an iterative procedure, dynamic soil properties play an important role. The shear modulus reduction curves and damping curves are usually obtained from laboratory test data (cyclical triaxial soil tests). The geotechnical properties of the individual soil layers should be assumed constant for each defined soil layer.

4.1 Spectral acceleration and PGA computed with SHAKE2000 program for equivalent linear modelling method

The following input parameters are necessary to be introduced in the programs used to compute the spectral amplification, by pseudo-linear site response analysis.

The interval seismic velocities V_S (m/s) and mean velocity values weighted with the thickness of each layer will be used for V_S (Bala et al., 2021). The thickness of each layer (m) will come from previous selected geologic models as well as the natural unit weight (kN/m^3) measured on probes (Bala et al., 2010).

The shear modulus ratio curves and damping curves versus shear strain (☒) are used in the programs like SHAKE2000 as built-in curves, although the program permitted the introduction of site-specific curves for a certain location.

The engineering procedure requires that the curves will be either determined by measurements applied on the rock samples collected from boreholes drilled in Bucharest City. Such conditions existed in the time of drilling the 10 boreholes down to 50 m depth (see Fig. 2). The samples were measured in laboratory conditions, preserving the humidity of the probes, and the results in the form of G/G0 and D/Do curves were reported by Bala et al. (2013).

The strong motion of the ground used as input can be a historic earthquake that has been recorded in the area, in order to reflect the characteristic period would have the arriving strong signal at the site. In theory strong signal should be recorded by a seismometer placed on the bedrock, because the modelling process assumes an input signal traveling from bedrock to surface level. These conditions existed at 3 locations in Fig. 2, where accelerometers were deployed in 3 boreholes at depths City Hall (PRI, 50 m), UTCB Tei (UT1, 70 m) and INCERC (INC, 100 m) were able to record the earthquake of 27.10.2004 (Mw = 6) in the Bucharest underground (Bala et al., 2013). The strong motion was applied at the base of the models considered to be the bedrock for modelling purposes. The type of the strong motion applied at the base of all geologic models was chosen as "inside" input motion.

4.2 Mean weighted seismic velocities of Quaternary layers in Bucharest

The mean weighted seismic velocities for the first 6 (of 7 types) of Quaternary layers were computed for all the 10 sites in Table 2, are as input for modelling with the program SHAKE2000. Using this program, we compute spectral acceleration response and transfer functions for every site in which measurements were performed.

Table 2. Mean weighted seismic velocities $\overline{\mathbf{V}}_{\mathbf{S}}$ for the first 6 (of 7 types) of Quaternary layers in 10 boreholes in Bucharest City (after Bala et al., 2009; Bala et al., 2021).

	Geologic stratum type							
	1	2	3	4	5	6		
Borehole site/symbol	**Mean weighted seismic velocities $\overline{V}_S$ [m/s]**						**V_{S30}**	**V_{S50}**
1. Tineret Park TINP	140	220	299	–	398	–	**263**	**304**
2. Ecology University EUNI	120	220	241	354	390	401	**286**	**326**
3. Astronomy Institute INAS	120	260	330	350	390	433	**283**	**320**

Borehole site/symbol	Geologic stratum type						V_{S30}	V_{S50}
	1	2	3	4	5	6		
	Mean weighted seismic velocities $\overline{V}_S$ [m/s]							
4. Titan2 Park TITAP	160	250	250	350	381	450	**299**	**341**
5. Motodrom Park MOTO	200	200	320	393	410	410	**288**	**327**
6. Student Park STUP	210	210	342	370	375	400	**295**	**319**
7. Bazilescu Park BAZI	160	160	317	390	408	—	**294**	**334**
8. Romanian Shooting Fd. FRTIR	210	330	350	400	400	—	**327**	**347**
9. Geologic Museum GEOM	180	310	322	376	380	—	**320**	**328**
10. NIEP site – NIEP	250	350	350	320	337	410	**326**	**338**
Average for all 10 sites	**169**	**252**	**320**	**367**	**386**	**417**		

In the last two columns we have computed $\overline{V}_S30$ and $\overline{V}_S50$ in each of the borehole and for the layers from layer 1 to layer 6, according to Eq. (1). The average for the 10 boreholes are $\overline{V}_S30 = 298{,}1$ m/s; $\overline{V}_S50 = 328{,}4$ m/s.

Values of $\overline{V}_S$ for the 30 m are between 263 m/s and 327 m/s and for $\overline{V}_S$ at 50 m are between 304 m/s and 347 m/s, so they belong to Class C according to the Romanian Seismic Design Code (UTCB, 2013). For the 70 m and 100 m depth intervals there are a few $\overline{V}_S$ values higher than 360 m/s but without surpassing 390 m/s. In the following subchapters we present the main characteristics of reference data (Bala et al., 2021).

4.3 Strong motion applied at the base of the geologic models

During this time a moderate earthquake just occured on 27.10.2004 (Mw = 5,8) in the Vrancea area, a depth of 40-42 km, which means aproximately at the Moho depth. The crustal earthquake of 27.10.2004 was one of the best documented earthquakes in Romania by a great number of records, either from broadband stations or accelerometers, in most cases being available all 3 components (one vertical and two horizontal).

The seismic event was recorded by the accelerometer network of National Institute for earth Physics (NIEP) placed in free field and also by the network of National Centre for Seismic Risk Reduction (NCSRR) with recordings at surface and in boreholes equipped with accelerometers (Aldea et al., 2006).

The 10 green dots in Fig. 5 represent the 10 boreholes which were performed and measured by down-hole measurements in 2007-2010 in the frame of NATO SfP project 981882 (Bala et al., 2010). The yellow and red dots are the boreholes in the administration of UTCB and NCSRR in which seismic measurements were performed (Aldea et al., 2006; Aldea et al., 2007). The 3 red dots mark the 3 boreholes that were equipped with accelerometers placed at 50, 70 and 100, depth and which were recording the movement of the 27.10.2004 crustal earthquake in the accelerometer network in Bucharest (Aldea et al., 2006).

The 3 stations equipped with borehole accelerometers at different depths which were chosen to supply the strong motion are: City Hall (PRI_EW) – 52 m; UTCB TEI (TEI_EW) – 78 m; INCERC (BBI_EW) – 100 m (see Table 3 and Fig. 6). The EW component is the strongest among the 2 horizontal recordings at each station and it was used as the strong signal applied at the base of the geological model considered.

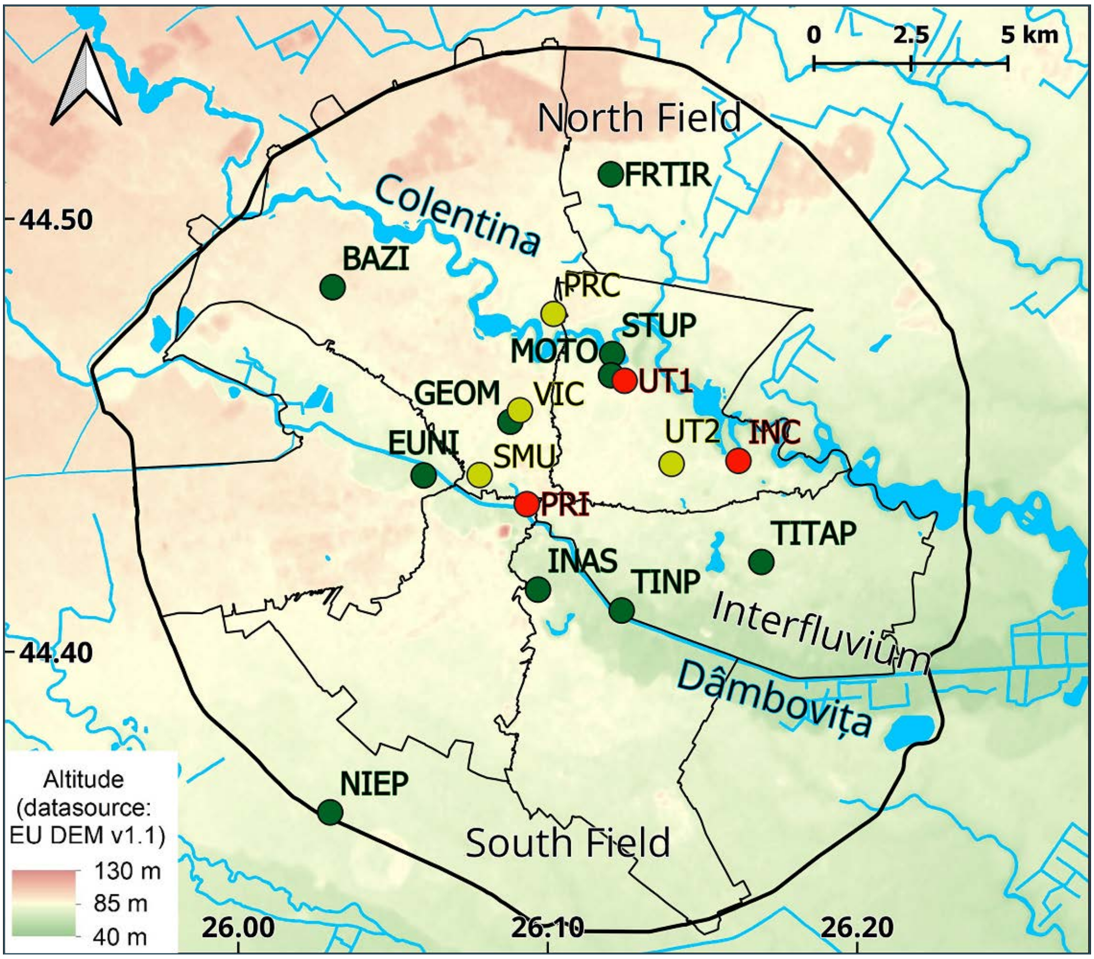

Figure 5. Map with area under investigation and measurement sites of the different projects and measurement campaigns. The metropolitan region of Bucharest, is mainly inside the characteristic ring road with a diameter of about 20-21 km. The 10 green dots are the 10 boreholes performed in the frame of NATO SfP project 981882. The yellow (4) and red dots (3) are the boreholes in the administration of UTCB and NCSRR in which seismic measurements were performed (by Aldea et al, 2006).

Table 3. Sites where both surface and borehole accelerometers are available in the seismic network of NCSRR are presented by Aldea et al. (2006).

Sites equipped with borehole accelerometers				Depth signal by accelerometer at the earthquake of 27.10.2004 in Bucharest
Borehole sites	Depth of sensor [m]	Average *Vs* [m/s]	Predominant period [s]	
City Hall – PRI	52	258	0.81	PRI_EW_52
UTCB TEI – UT1	78	349	0.89	TEI_EW_78
NCSRR/ INCERC – INC	100	364	1.54	BBI_EW_100

These models were able to give us the spectral amplification from the depth to the surface for this earthquake in 17 points in Fig. 5. The spectral acceleration recorded and applied as input signal are PRI_EW_52 (for 50 m depth); TEI_EW_78 (for 70 m depth); BBI_EW_100 for 100 m depth, from Table 3 and Fig. 6.

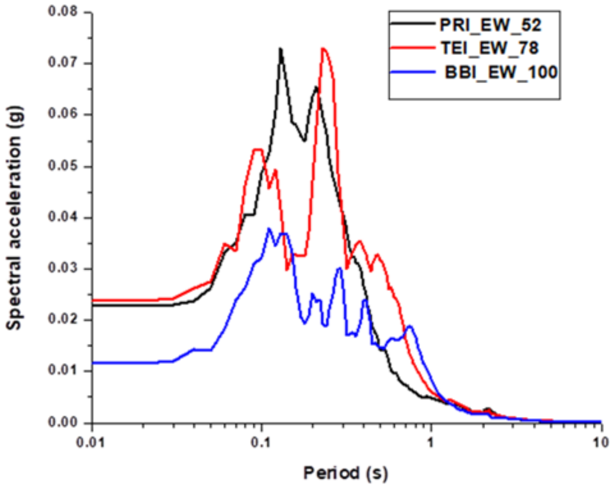

Figure 6. Spectral acceleration of the 3 strong motions chosen for modelling: PRI_EW – 52 m; TEI_EW – 78 m; BBI_EW – 100 m. The strong motions were recorded during the crustal earthquake from 27.10.2004 felt on a large area, including Bucharest.

5. Results of applying the linear equivalent analysis for different depths of the considered geological model in Bucharest city

At that time there were available a set of accelerometers operated by NIEP and NCSRR, both field accelerometers and sensors placed at the bottom of some boreholes in the Bucharest city.

Several depths at which the initial strong motion was applied were considered: 50 m; 70 m; 100 m. This was possible because accelerograms recorded at different depths (including at surface) were available during the earthquake of magnitude of 27.10.2004.

First for the model down to 50 m depth, the strong motion recorded at Cityhall (PRI_EW_52, Table 3) is used.

For the next modeling of the spectral amplification at surface, the strong motion recorded at 70 m depth TEI_EW (EW component of recorded acceleration at UTCB_TEI location) is used.

The boreholes in Table 4 have a limited depth of 50 m. In this case the geologic model from 50-70 m depth was completed from other boreholes, as the most appropriate model and the strong motion was placed at the maximum depth of the model –70 m. The supplementary boreholes are described in the pool of Shear-wave velocity database by Bala et al. 2021.

5.1 Results of spectral amplification determination with real ground motion models at 50 m

The first 10 boreholes in Table 4 have a limited depth of 50 m. In the rest of the boreholes in Table 4, the geological model was considered down to 50 m depth and the strong motion recorded at City Hall (PRI_EW_52) is used.

If we consider a comparison between different locations, we can observe a ratio of 2.28, between the highest spectral amplification (0.32g) and the lowest value 0.14g. The Spectral Amplification Ratio (SAR) are also calculated. These spectral ratios were defined as the ratio between the spectral acceleration determined at the surface and the spectral acceleration of the strong motion applied at a depth of 50 m (Table 4) or 70 m (Table 5).

$$\mathrm{SAR} = \mathrm{SA}/\mathrm{SA}_0 \tag{3}$$

Table 4. Amplitude spectral acceleration for 17 sites in Bucharest with real ground motion models (50 m). Spectral acceleration ratio (SAR) computed with Eq. (3).

Borehole 50 m depth	Label		Period	
			$T_1 = 0.12$ s	$T_2 = 0.2$ s
Astronomy I st.	INAS	SA(g)	0.26	0.42
		SAR	3.74	6.50
Ecology Univ.	EUNI	SA(g)	0.30	0.48
		SAR	4.32	7.43
Bazilescu Park	BAZI	SA(g)	0.32	0.4
		SAR	4.60	6.19
Student Park	STUP	SA(g)	0.24	0.34
		SAR	3.45	5.26
Motodrom Park	MOTO	SA(g)	0.24	0.34
		SAR	3.45	5.26
Titan2 Park	TITAP	SA(g)	0.32	0.38
		SAR	4.60	5.88
Tineret Park	TINP	SA(g)	0.24	0.30
		SAR	3.45	4.64
Geologic Museum GEOM	GEOM	SA(g)	0.19	0.28
		SAR	2.73	4.33
Romanian Shooting Fed.	FRTIR	SA(g)	0.14	0.22
		SAR	2.01	3.40
NIEP – Magurele	NIEP	SA(g)	0.18	0.24
		SAR	2.59	3.72
Cityhall Bucharest	PRI	SA(g)	0.23	0.33
		SAR	3.40	5.20
Victoria Square	VIC	SA(g)	0.25	0.35
		SAR	3.57	5.38
Civil Protection	PRC	SA(g)	0.21	0.30
		SAR	3	4.62
UTCB Tei	UT1	SA(g)	0.17	0.26
		SAR	2.43	4
UTCB Pache	UT2	SA(g)	0.25	0.23
		SAR	3.57	3.54
Municipal hospital	SMU	SA(g)	0.14	0.15
		SAR	2	2.31
NCSRR/INCERC	INC	SA(g)	0.15	0.17
		SAR	0.21	0.23

The spectral acceleration values in Table 4 (for the periods T1 = 0.12 s and T2 = 0.2 s) are represented as isolines on the map of Bucharest in Figs. 7a and 7b.

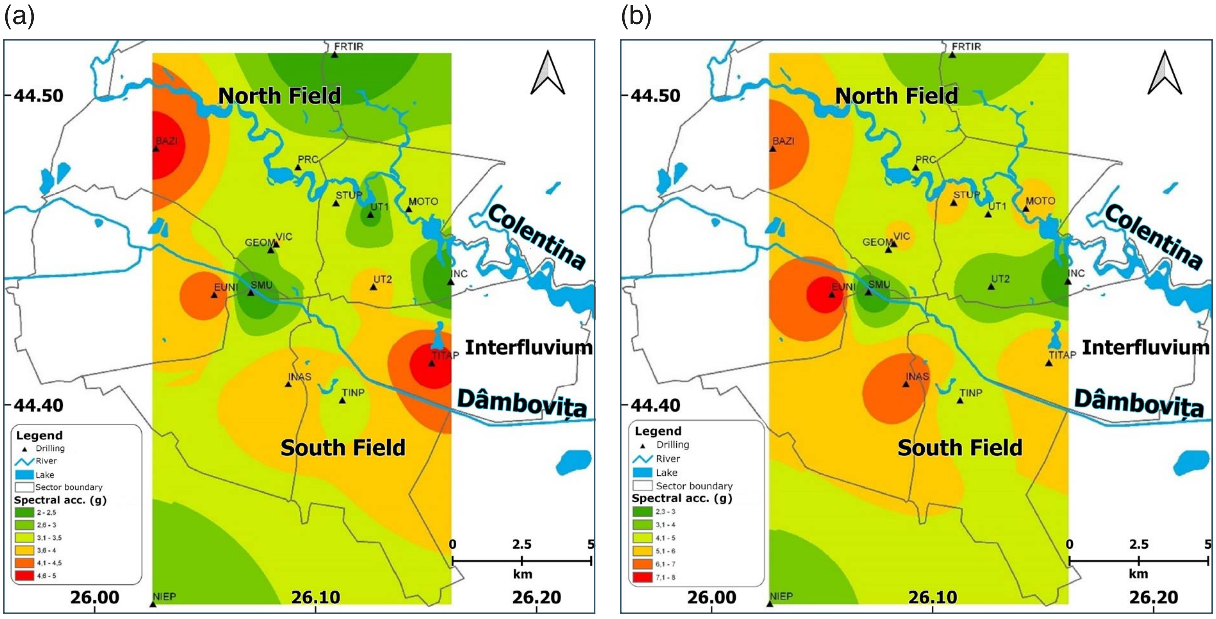

Figure 7. Map of Spectral amplification ratio in Bucharest for 50 m depth: (a) T1 = 0,12 s; (b) T2 = 0,20 s (after Table 4).

5.2 Results of spectral amplification determination with real ground motion models at 70 m

In this case the geologic model for the first 10 boreholes was completed from other boreholes from 50-70 m depth, as the most appropriate model and the strong motion was placed at the maximum depth of the model –70 m. The supplementary boreholes are described in the pool of Shear-wave velocity database by Bala et al. 2021.

For the strong motion at 70 m depth it was considered TEI_EW_78, recorded at 78 m depth in UT1 site (Table 3).

From Table 5, we can see the maximum values of the spectral accelerations corresponding to the first two values of the period of T1 = 0.12 s; T2 = 0.25 s. The absolute values for T1 are between 0.1 g-0.17 g. The amplifications corresponding to the movement applied to the base of the geological package (SA at 70 m depth) are from 1.9 to 3.86, for T1. The highest absolute values are recorded for T2, of 0.20-0.41 g.

The corresponding amplifications have the highest values from 2.8-6.19 in this spectral range. If we consider a comparison between different locations, we can observe a ratio of 2.15 to 1 between the Univ. Ecology Univ. which has the highest spectral amplification (0.416g at T2) and R.S. Federation which has the lowest value –0.193 g at T2. The spectral SAR (Spectral Amplification Ratio) ratios were also calculated. These spectral ratios were defined as the ratio between the spectral acceleration determined at the surface and the spectral acceleration of the strong motion applied at a depth of 70 m.

Based on the information in Table 5, the spectral amplification map (SAR) was created for the first period and second period in the Fig. 8. Thus, we have large amplifications up to 3.9 in the south and west, medium amplifications in the center and northeast and small amplifications up to 2 to the north and east (Fig. 8a). For the second period (0.25 s in Table 5) the amplifications are higher, up to 6 in the south and west, with a peak around the location of the Ecology University. Lower values of 2.1-3 are in the central and northeastern part, with a minimum at Victoria Square (Fig. 8b).

Table 5. Amplitude spectral acceleration for 16 sites in Bucharest with real ground motion models (70 m). Spectral acceleration ratio (SAR) computed with Eq. (3).

Borehole 70 m depth	Label		Period		
			$T_1 = 0.12$ s	$T_2 = 0.25$ s	$T_3 = 0{,}62$ s
Astronomy Inst.	INAS	SA(g)	0.154	0.234	0.128
		SAR	3.133	3.488	5.663
Ecology Univ.	EUNI	SA(g)	0.158	0.416	0.132
		SAR	3.216	6.192	5.810
Bazilescu Park	BAZI	SA(g)	0.161	0.255	0.059
		SAR	3.866	3.793	2.617
Student Park	STUP	SA(g)	0.111	0.205	0.070
		SAR	2.667	3.048	3.094
Motodrom Park	MOTO	SA(g)	0.130	0.269	0.097
		SAR	2.633	4.013	4.258
Titan2 Park	TITAP	SA(g)	0.171	0.393	0.149
		SAR	3.478	5.552	6.554
Tineret Park	TINP	SA(g)	0.147	0.246	0.117
		SAR	2.999	3.674	5.146
Geologic Museum GEOM	GEOM	SA(g)	0.120	0.202	0.088
		SAR	2.453	3.011	3.908
Romanian Shooting Fed.	FRTIR	SA(g)	0.094	0.193	0.082
		SAR	1.906	2.875	3.624
NIEP – Magurele	NIEP	SA(g)	0.150	0.302	0.107
		SAR	3.050	4.505	4.473
Victoria Square	VIC	SA(g)	0.09	0.08	0.06
		SAR	2.27	1.69	1.83
Civil Protection	PRC	SA(g)	0.11	0.10	0.06
		SAR	2.67	2.16	2.12
UTCB Tei	UT1	SA(g)	0.08	0.10	0.05
		SAR	2.13	2.16	2.12
UTCB Pache	UT2	SA(g)	0.13	0.10	0.06
		SAR	3.24	2.17	2.77
Municipal hospital	SMU	SA(g)	0.07	0.13	0.07
		SAR	1.67	2.69	2.36
NCSRR/INCERC	INC	SA(g)	0.07	0.09	0.06
		SAR	1.61	1.85	2.20

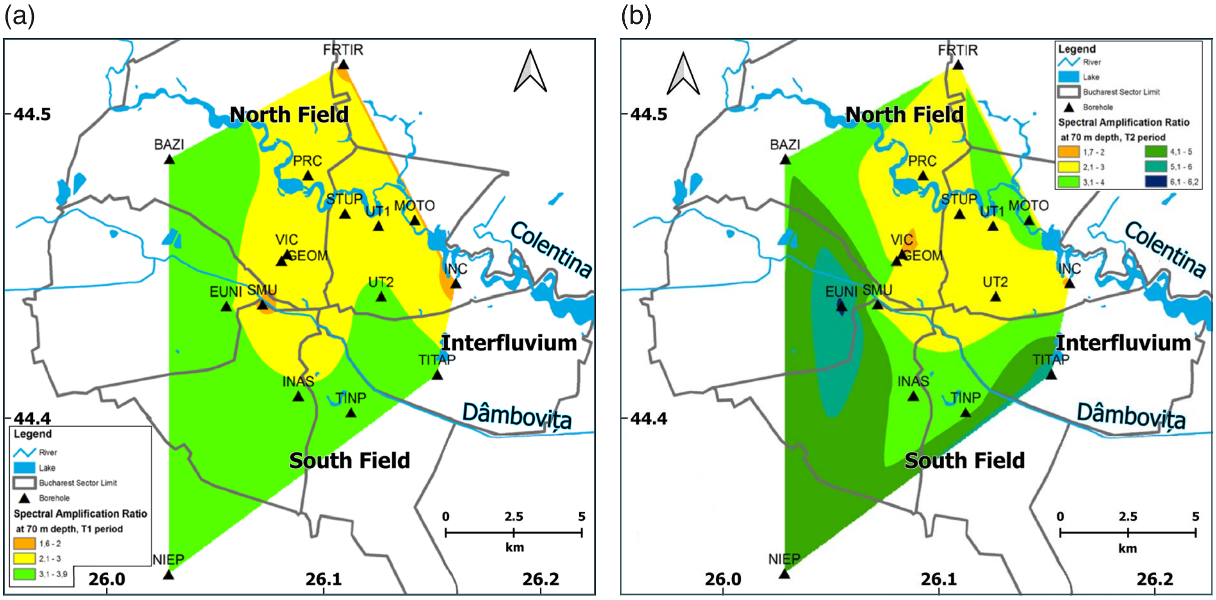

Figure 8. Map of Spectral amplification ratio in Bucharest for 70 m depth: (a) T1 = 0,12 s; (b) T2 = 0,25 s (in Table 5).

5.3 Map of the PGA recorded at surface in comparison with PGA map obtained by modelling from 70 m depth geological model

The earthquake of 2004 (Mw = 6) was taken as a basis for modeling, as it was recorded at several area stations at ground level, as well as several records in boreholes.

It was created the possibility of direct comparison of PGA values recorded at the surface (Fig. 8) with the map of PGA values obtained from modeling between 70 m depth to the surface (Fig. 9).

First it should be noted that the two maps cover almost the same range of values up to 0.075-0.078 g. This is remarkable and it means that we can provide a certain degree of confidence to modeling applied on 70 m depth to surface models.

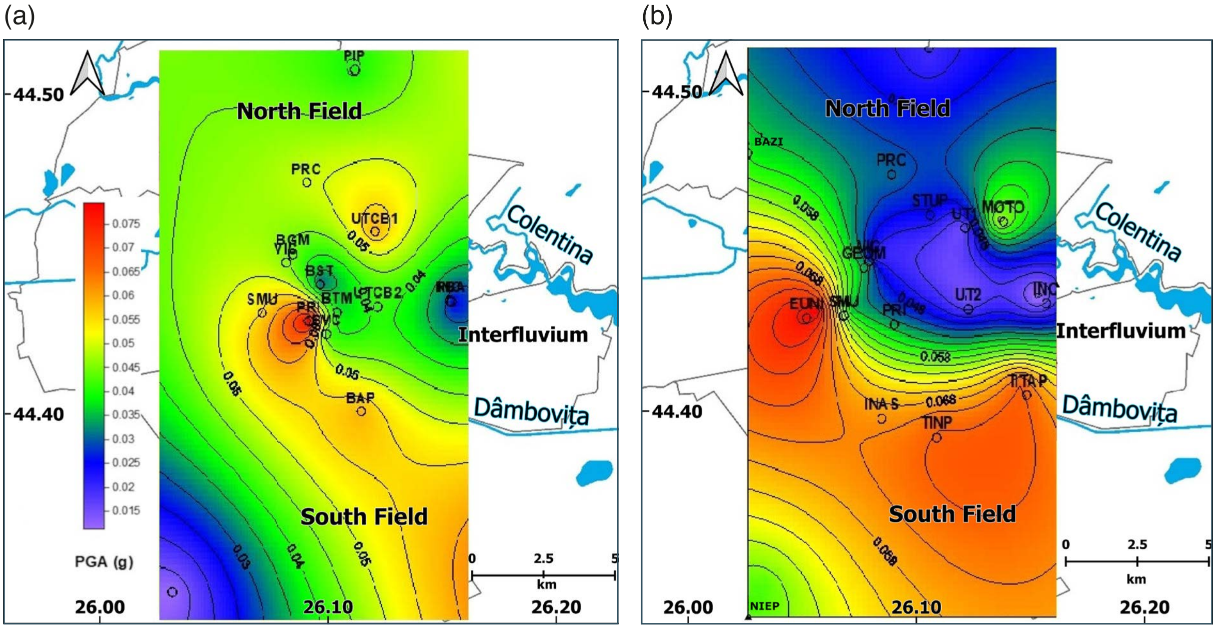

Figure 9. (a) Map of the PGA recorded at surface during the 27.10.2004 earthquake; (b) PGA map obtained by modelling from 70 m depth to surface using a strong motion recorded during the 27.10.2004 earthquake (BBI_EW in Table 3).

Map of the PGA values modeled at surface in Fig. 9, shows a much clearer division, medium and large values of the southwest to the center, followed by a rapid decrease band in the central and lower values towards the northeast. In terms of PGA values recorded at the surface map in Fig. 9a, it starts at much lower 0.015g southwest (NIEP), followed by an increase towards the center to maximum (PRI) and a decrease in medium values to north-east and local low value around INC station.

Different aspects of the map in Fig. 9a in respect with the map in Fig. 9b can be generated by the fact that in general surface stations do not coincide with locations where modeling was performed from 70 m to the surface (Fig. 9). In Bucharest the geologic model might change very quickly from one location to the other even at 200 m distance (Bala et al., 2022).

5.4 Spectral acceleration models computed in 7 locations in central Bucharest with geological models down to 100 m depth

The geological models considered were those in the previous chapters, down to 70 m depth and were completed down to 100 m with models corresponding to other nearby drillings, from which the shearwave velocities for each layer were also recorded. For the INC_140m drilling we had the real geological and geophysical model, based on the drilling measurements performed by UTCB, down to 140 m depth.

For the INC_140 m drilling we had the real geological and geophysical model, based on the drilling measurements performed by UTCB, up to 140 m depth. The evolution of the acceleration in depth shows a moderate increase up to 30 m depth, followed then by a sharp increase up to the surface, from 0.012g to values of 0.02-0.035 g. The spectral acceleration graphs in Fig. 10 show 2 maxima: at 0.12 s and at 0.3 s, in agreement with the spectrum of the strong motion applied.

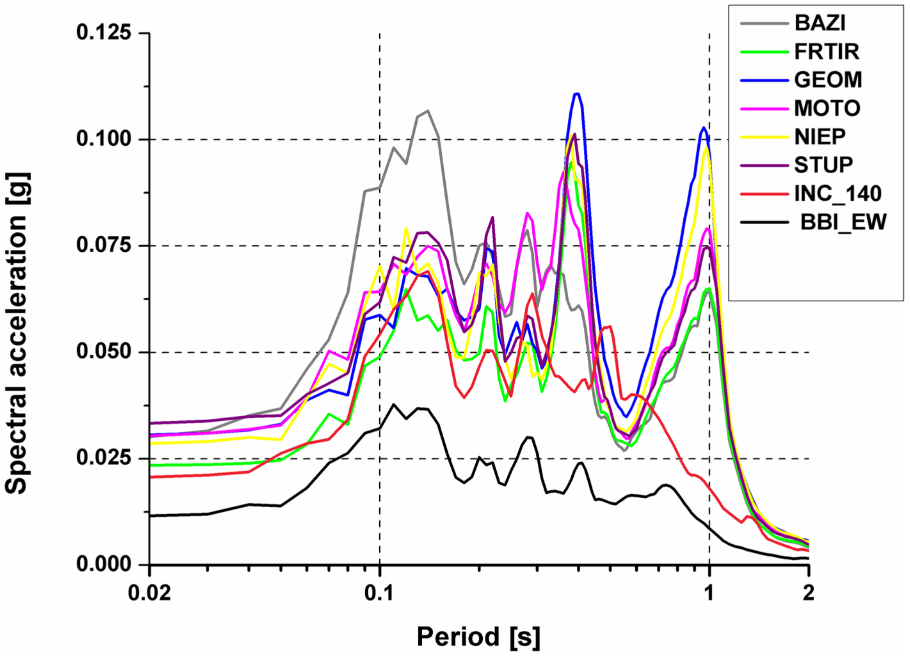

Figure 10. Spectral acceleration computed for the 7 models down to 100 m depth in central Bucharest. For the position of the boreholes see Fig. 5. After Bala A., 2014.

The curves of the amplification ratios (Fig. 10) calculated for the 7 models in Bucharest (Table 6) show that the amplifications are no longer so high for the second characteristic frequencies. Also, these characteristic frequencies may depend on the measurement location: for the NIEP location they are clearly shifted. It is clear that geological and geophysical models are becoming increasingly complex in the depth and tend to differentiate themselves more with the increase in the thickness of the considered layer package.

Table 6. Spectral acceleration amplitude for 7 locations in Bucharest as well as the Spectral amplification ratio (from 100 m depth to surface).

Borehole model 100 m	Label		Period		
			$T_1 = 0.13$ s	$T_2 = 0.25$ s	$T_3 = 0.35$ s
Bazilescu Park	BAZI	SA(g)	0.112	0.08	0.062
		SAR	3.03	2.666	2.481
Student Parc	STUP	SA(g)	0.08	0.052	0.10
		SAR	2.164	1.733	4
Motodrom Parc	MOTO	SA(g)	0.075	0.081	0.087
		SAR	2.028	2.702	3.484
INCERC 140	INC	SA(g)	0.07	0.062	0.060
		SAR	1.893	2.070	2.403
Muzeul Geologic	GEOM	SA(g)	0.06	0.060	0.12
		SAR	1.623	2	4.807
F.R.Tir	FRTIR	SA(g)	0.062	0.054	0.09
		SAR	1.677	1.801	3.610
NIEP – Magurele	NIEP	SA(g)	0.07	0.052	0.11
		SAR	1.893	1.736	4.405

For the last 6 analyzed boreholes in Table 7 (below), the PGA values computed from 70 m depth to surface are in the range of 0.039-0.061 g. In this case it is observed that the results depend largely on the surface soil layers, responsible for amplifying the maximum acceleration recorded at surface.

However, one can observe the correspondence between the computed PGA values and those recorded at 5 of the 6 points where the modeling was performed using the EERA program, especially at the PRC, SMU and INC stations, where the results are matching.

Table 7. PGA values obtained at surface: from models from 70 m to surface; from models from 100 m to surface; PGA recorded at surface at the 27.10.2004 earthquake in Bucharest.

Borehole	Label	PGA1 (g) from 70 m depth to surface	PGA2(g) from 100 m depth to surface	PGA(g) Recorded at surface
Astronomy Inst.	INAS	0.0681	—	
Ecology Univ.	EUNI	0.0797	—	
Bazilescu Park	BAZI	0.0551	0.0302	
Student Park	STUP	0.0476	0.0333	
Motodrom Park	MOTO	0.0612	0.0304	

Borehole	Label	PGA1 (g) from 70 m depth to surface	PGA2(g) from 100 m depth to surface	PGA(g) Recorded at surface
Titan2 Park	TITAP	0.0720	—	
Tineretului Park	TINP	0.0716	—	
Geologic Museum	GEOM	0.0522	0.0306	
F.R.Tir	FRTIR	0.0448	0.0234	
NIEP – Magurele	NIEP	0.0580	0.0286	
Civil Protection	PRC	0.051		0.0501
Municipal Hospital	SMU	0.054		0.0453
UTCB – Tei	UTC1	0.042		0.0595
UTCB – Pache	UTC2	0.061		0.0417
Victoria Square	VIC	0.045		—
INCERC/NCSRR	INC	0.039		0.0302

5.5 Discussion upon the influence of input data on the results of modeling

Equivalent linear analysis method is an optimal method to be used for quantitative zoning of cities. It encompasses in addition to specific geotechnical input some nonlinear elements characteristic to sedimentary rocks that have a great influence on the results. The results obtained with the program SHAKE 2000 depends largely on the basis of input data specific to the geotechnical database with values measured in situ.

Regarding the input data, the shear-wave velocities have an important part in the modeling, the results were commensurate with VS2. Geophysical measurements conducted have provided reliable values for the 7 complex Quaternary errors up to 10% for transverse wave velocity (Bala et al., 2023b).

It is obvious that in a large and crowded city multiplying these points of measurements for V_S by classical methods is difficult to continue. They should be supplemented by indirect measurements of seismic velocities in depth, benefitting by modern methods of computation, as those using seismic noise and Rayleigh waves recordings and multichannel recordings over a network.

Acceleration response spectra calculated for the chosen locations in Bucharest, down to 70 m depth, have many similar issues due to relatively uniform velocity profile (transverse seismic wave velocity and thickness of sedimentary layers) and also because of the curves G/Gmax and curves depreciation taken into account. They depend largely on the strong motion spectra applied to the model considered, as well as the depth of the models, which can be considered existing bedrock. Results are closer to reality are obtained if the model considered reaching a depth of 70 m or more.

Spectral amplification maps obtained for models from 70 m depth show peaks of amplification for two main periods. For the first period amplifications are up to 4 in the South and West, the average amplification in the center and northeast and small amplification north and east. For the second period map generally shows the same trend, but the amplification is higher with a peak around 6.

The map of the maximum accelerations recorded (PGA) is presented for the earthquake 27.04.2004. This map was compared with the maximum acceleration achieved by modeling, from a depth of 70 meters to surface. The last one has a much clearer division, medium and large values of the southwest to the central part followed by a rapid decrease in the band central and northeast low values. It is remarkable though that modeled surface accelerations are obtained in the same range of values up to 0,075-0,078 g. This allows us to consider that modeling from 70 m and 100 m depth to the surface are much closer to the actual values, compared to modeling at shallower depths (Bala 2014).

The level of geological profile considered "seismic bedrock", where the strong signal must be applied, is dependent greatly on the depth of the geological and geotechnical models considered.

Modeling performed at the 3 depth levels (50 m; 70 m; 100 m) demonstrate that deeper models are better in order to explain the PGA values recorded at surface (Bala, 2014).

In the present paper modeling from 70 m 100 m depth to surface are performed and the results are compared with the spectral acceleration obtained at surface in 17 points placed in Bucharest central part. The results are coherent with the acceleration measured at surface of the earthquake from 27.10.2004 (Mw = 6).

Seismic noise analyses highlights the resonance of interest in the city of Bucharest. When the seismic radiation spectrum coinciding with that of the local pack of sedimentary package the maximum destructive effect occurs. Even in the case of relatively strong earthquakes (Mw > 7), if they do not emit enough energy in the domain of the spectral resonance (0.2-1.6 Hz), the seismic waves effects in Bucharest effects are not catastrophic, as it was presented by Aldea et al. 2006 and Lungu et al. 2007, it is apparently the case of the events of August 30, 1986 (Mw 7.1) or May 30, 1990 (Mw 6.9). Conversely, when the seismic source spectral content coincides with the fundamental period of the local response, then the effects are severe (the case of March 4, 1977 catastrophic event).

6. Conclusions

1) The shallow geology of Quaternary layers in Bucharest City is rapidly changing from one point to another in only a few hundreds of meters not only in the thickness of the layers, but also in the geotechnical properties of each layer. A comprehensive database of the geologic layers in Bucharest was assembled by Toma-Danila et al. (2025), based on the latest geologic model in Bucharest underground, down to 100 m depth with a few measurements down to 200 m depth.
2) The shear-wave velocities obtained by different methods and within several research projects are recommended to be used to determine mean weighted values for each of the seven Quaternary layers in the area of Bucharest. These shear-wave velocities values are organized by Bala et al. 2021 in a database, which gathered all the results of field measurements in Bucharest in the last 2 decades. The model obtained for the distribution of these V_S velocities in the underground of Bucharest is presented at large in Bala et al. 2023b.

   The number and quality of the databases of the 3D geological data down to 70 m depth is completed with the presentation of the V_S velocity values assigned to every geological layer and more capable to sustain further investigations in the direction of seismic site effects study in Bucharest city and other cities in Romania directly exposed to strong Vrancea earthquakes (see also Bala et al., 2023a).
3) Shear modulus reduction curves and damping curves have a great influence on the spectral amplification of the soil computed for a certain location. A collection of these curves are presented by Bala et al. (2013) based on laboratory measurements on sedimentary sediments in the 10 boreholes performed in Bucharest (Fig. 2).
4) Because of the lack of an outcropping bedrock in the Bucharest area, a real seismic signal recorded in a borehole should be used as input signal. The strong seismic signal is considered the same for the entire study area. That is what we have begin to apply to our models in Bucharest underground in the present study.

   Some other computed strong motions can be used, having the same frequency content as the recorded strong signals. However it should be noted that the frequency of the strong motion has an important variability at the last strong earthquakes recorded in Bucharest with Mw greater than 7 (4 March 1977 event) (see Chaper 10).
5) By mapping and interpreting the newly assembled geological model, as well as the assigned geophysical values (shearwave velocity), we begin to compute the spectral amplification values at surface, using the data recorded at the earthquake from 27.10.2004 at surface and in the depth.

   This spectral modelling is applied to deeper models than the uppermost 30 m, and considering the 50 m, 70 m and 100 m depth intervals, where we have now an important database for weighted mean shearwave velocities (V_S) in the depth. The results attested the importance of this action and we present solid results that the values computed for the deeper models are closer to the computed surface values, especially for the depth intervals of 70 and 100 m depth.

The spectral acceleration values as well as the PGA computed at surface are based first on new database of geological model and assigned geological emerging in the last years, as well as on an extended measuring of the strong motion values of an earthquake at surface and also in the depth down to 100 m depth.

In order to obtain an adequate microzonation, the ideal method would be to obtain such measurements in a grid of points with a distance of at least 0,2-0,5 km interspace, which now can be done using the 3D databases, one for the geological model and the second for V_S distribution in the Bucharest underground which were assigned to specific geological complexes.

Data availability statement. The shear-wave velocity database in Bucharest city is published can be retrieved from Bala et al. (2021). Shear-wave velocity database for Bucharest. Mendeley Data, Version 2 https://data.mendeley.com/datasets/jncnc6fng9.

The geologic model underneath Bucharest city is published and can be retrieved from Toma-Danila et al. (2025). Mendeley Data, V1, https://data.mendeley.com/datasets/pkjpyjghk9.

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