Quantitative modelling of seismic site amplification in an earthquake-endangered capital city: Bucharest, Romania

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Abstract Bucharest, the capital city of Romania, with more than 2 million inhabitants, is considered as a natural disaster hotspot by a recent global study of the World Bank and the Columbia University (Dilley M et al. Natural disaster hotspots: a global risk analysis. International Bank for Reconstruction and Development/The World Bank and Columbia University, Washington, DC in 2005). Therefore, it is classified as the second metropolis in Europe, after Istanbul, subjected to important losses in the case of a destructive Vrancea earthquake with moment magnitude greater than seven. Four major earthquakes with moment magnitudes between 6.9 and 7.7 hit Bucharest in the last 68 years. The most recent destructive earthquake on March 4, 1977, with a moment magnitude of 7.4, caused about 1,500 casualties in the capital alone. All disastrous intermediate-depth earthquakes are generated within a small epicentral area—the Vrancea seismogenic region—about 150 km northeast of Bucharest. Thick unconsolidated sedimentary layers below Bucharest amplify the arriving seismic waves causing severe destruction. Ten 50-m-deep boreholes are drilled in the metropolitan area of Bucharest in order to obtain a unique, homogeneous dataset of seismic, soil-mechanic and elasto-dynamic parameters. Cores for dynamic tests were extracted, and vertical seismic profiles were performed to obtain an updated site amplification model related to earthquakes waves. The boreholes are placed near former or existing seismic station sites to allow a direct comparison and calibration of the borehole data with previous seismological measurements. A database containing geological characteristics for each sedimentary layer, geotechnical parameters measured on rock samples, P- and S wave velocity and density for each sedimentary layer is set up, as a result of previous papers with this subject. Direct data obtained by the geophysical methods in the new boreholes drilled in Bucharest City, as well as from laboratory measurements, are used as input data in the program SHAKE2000. Results are obtained in the form of spectral acceleration response, and peak acceleration in depth is computed for every site in which in situ measurements were performed. The acceleration response spectra correspond to the

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shear-wave amplifications due to the models of sedimentary layers down to (a) 50 m depth; (b) 70 m depth; and (c) 100 m depth. A comparison of the acceleration response spectra obtained by modelling at surface with a real signal recorded at surface is obtained in three sites, as test sites for the three depths considered, in order to calibrate the results obtained by equivalent linear method of the seismic site response.

Keywords Destructive earthquakes · Seismic site amplification · Borehole seismic measurements · Modelling by equivalent linear approach

1 Introduction

Bucharest is situated in a Miocene alluvial basin with thick sedimentary formations, responsible for seismic site effects. Beneath Bucharest, the Moesian platform is composed of two main structural elements: a 8–10 km deep sedimentary foredeep basin and the crystalline basement (Polonic 1996; Hauser et al. 2001). The sedimentary cover can be divided into three major units. The top Quaternary layers consist of partly unconsolidated and water-saturated fluvial sediments from the Colentina and Dambovita rivers (Liteanu 1952). Their total thickness varies from 200 m in the south to 300 m in the north (Kienzle et al. 2006). Below, Cenozoic sediments reach thicknesses of about 0.7–1.5 km which are followed by consolidated Mesozoic and Palaeozoic sedimentary rocks. Using borehole data Bucharest Municipality GEO-ATLAS (2008) mapped the interface between Creta- ceous and Tertiary sediments and found a significant dip from south (500 m) to north (1,600 m). The related increase in sediment thickness towards northeast is assumed for most Cenozoic layers in the foredeep basin around Bucharest, except for the shallowest deposits in the upper 50–100 m depth. These shallow layers exhibit lens-like structures and varying thicknesses of the single layers.

During the last century, four major Vrancea earthquakes occurred on November 10, 1940 (Mw = 7.7); March 4, 1977 (Mw = 7.4); August 30, 1986 (Mw = 7.1) and May 30, 1990 (Mw = 6.9). Moment magnitudes are taken from the ROMPLUS catalogue (Oncescu et al. 1999). The former two lead to disastrous impact on Romanian territory. According to official data in the March 4, 1977 event, 1570 people died, 11,300 were injured and 32,500 residential and 763 industrial units were destroyed or seriously damaged. Bucharest with its high-risk potential is located about 100–130 km southwest of the epicentral Vrancea region. Typical hypocentral distances of the intermediate-depth events that determine the hazard for the city are in the range of 150–180 km. Compared to such distances, the spatial extent of Bucharest is relatively small. The geometry of intermediate-depth seismicity in Vrancea region leads to almost vertical raypaths beneath the recording stations in Bucharest.

2 Seismic bedrock and engineering bedrock in Bucharest area

The depth of the discontinuity corresponding to the seismic bedrock is well known from drilling and geological studies. This discontinuity corresponds to the Cretaceous/Neogene interface which is dipping from about 500 m in the south to about 1,500–1,600 m in the northern part of Bucharest (Bucharest Municipality GEO_ATLAS).

Sèbe et al. (2009) studied Love waves from eight Romanian seismic events. Using a frequency–wave number analysis, they found that the Love wave dispersion varies distinctly from north to south. At the base of the Tertiary, higher phase velocities are found in the north compared to the south.

Near surface shear-wave velocity was fixed around 400 m/s across the city. This shear-wave velocity range is close to other published values from borehole measurements (Bala et al. 2006) or shallow shear-wave refraction seismics (von Steht et al. 2008). The shear-wave seismic velocities continuously increase from 400 m/s in the shallow layers to about 1,000 m/s at 1,000 m depth in the south and to 1,345 m/s at 1,500 m depth in the north of Bucharest (Sebe et al. 2009). The average gradient in the Neogene sediments has almost no lateral variation, and values of 0.56–0.64 s^{-1} were found (Sebe et al. 2009). The proposed two-layered models for the sediments underneath Bucharest have similar average V_S values as the seismic refraction model by Raileanu et al. (2005), but contain more details, especially lateral variations which are resolved for the first time.

In the viewpoint of Earthquake Engineering, it has been proposed to use a shallower interface for the site-effects modelling, of which underlying stratum has from 300 to 700 m/sec of the shear-wave velocity. This interface is called "engineering bedrock" (International Handbook of Earthquake and Engineering Seismology 2003).

The definition of the engineering bedrock (EB) can depend on the purpose of the study, but usually it is Tertiary rock or hard Pleistocene rock commonly found in the studied region with some constraints on its geotechnical and geophysical properties (International Handbook of Earthquake and Engineering Seismology 2003).

Satoh et al. (1995) defined the EB as the layer of sedimentary rock of Pliocene or earlier age with S wave velocity of 500 m/s or larger and standard penetration test (SPT) blow count of 50 or more (Satoh et al. 1995).

In the majority of the analyses, the EB was defined within Neogene or older geological formations, with shear-wave velocity of $V_S = 500$–550 m/s and mass density $\rho = 2,200$ kg/m^3.

The EB was proposed in Bucharest area at the upper limit of Fratesti A layer (Mândrescu et al. 2004), for which shear-wave seismic velocities in the domain of 500–550 m/s were documented (Bala et al. 2007, 2009b).

One can observe that the proposed interface does not comply with any of the geotechnical requirements which are usually imposed for EB.

1. Although there is documented a shear-wave velocity of 500–550 m/s at this level, this value is reached through a continuous gradient, which is continuing down to 1,000 m depth (Sebe et al. 2009) all over the city and not by an important step in shear-wave velocities (Bala et al. 2011).
2. The Fratesti layer complex is composed of 3 principal layers of gravel which contains important aquifers, separated by layers of compact shale, which have obvious heterogeneous characteristics. (Ciugudean-Toma and Stefanescu 2006).
3. The upper interface of Fratesti layers is dipping from south to north, from 100 m depth at Magurele (southern Bucharest) to about 200–250 m in Otopeni (northern part of Bucharest). So the interface is not horizontal as it is assumed for the EB, but it has a slight gradient.

After all these observations, supported by recent studies, it can be concluded that the EB cannot be fixed in the underground of Bucharest City, since there is no layer having such characteristics, at least in the first 200–300 m depth of sedimentary package. Any layer that is introduced in the modelling as EB and where the strong motion is applied during

modelling process should be considered with much care. The single interface that can be candidate for EB is the Cretaceous/Tertiary interface where the seismic bedrock is documented both by geologic methods and regional observations of shear-wave velocity (Raileanu et al. 2005).

For geologic reasons above, it is believed that the observed variability in ground motion within Bucharest City is predominantly caused by site effects. The regional geology does not suggest significant basin or basin-edge effects (Polonic 1996). As Bucharest is built on the fluvial planes of the Danube, no significant surface topography exists (Polonic 1996). Thus, the simple model with several horizontal layers can be applied with confidence.

In the present paper, the base of the geologic models is considered to be the EB for modelling purposes. The input strong motion is applied as 'inside motion' at 50, 70 and 100 m depth, corresponding with the depth of one-dimensional geologic models available.

3 Seismic measurements performed in Bucharest City

The latest results in the shear-wave velocity measurements were obtained in the frame of the NATO SfP Project 981882 (2006–2009), reported by Bala et al. (2007) and the Romanian project 31-038 (2007–2010), reported by Bala et al. (2009b, 2011). The results are summarized in Table 1. The mean seismic velocities computed for the 10 particular sites in Table 1 are representative values for the 6 types of Quaternary sedimentary layers in Bucharest City, the 10 sites being spread mainly in the city centre (Fig. 1).

Mean weighted values for V_P and V_S are computed for each site (borehole) according to the following formula:

$$\bar{V}_S = \frac{\sum_{i=1}^{n} hi}{\sum_{i=1}^{n} \frac{hi}{V_{Si}}} \qquad (1)$$

Table 1 Mean weighted shear-wave velocities for the first 6 (of 7 types) of Quaternary layers in 10 boreholes in Bucharest City

Borehole site/symbol	Geologic stratum type						V_{S-30}
	1	2	3	4	5	6	
	Mean weighted seismic velocity V_S (m/s)						
1. Tineret Park TINP	140	220	299	–	398	–	263
2. Ecology University EUNI	120	220	241	354	390	401	286
3. Astronomy Institute INAS	120	260	330	350	390	433	283
4. Titan2 Park TITAP	160	250	250	350	381	450	299
5. Motodrom Park MOTO	200	200	320	393	410	410	288
6. Student Park STUP	210	210	342	370	375	400	295
7. Bazilescu Park BAZI	160	160	317	390	408	–	294
8. Romanian Shooting Fed. FRTIR	210	330	350	400	400	–	327
9. Geologic Museum GEOM	180	310	322	376	380	–	320
10. NIEP site NIEP	250	350	350	320	337	410	326
All sites	169	252	320	367	386	417	

Description of the geologic layers is given by Ciugudean-Toma and Stefanescu (2006)
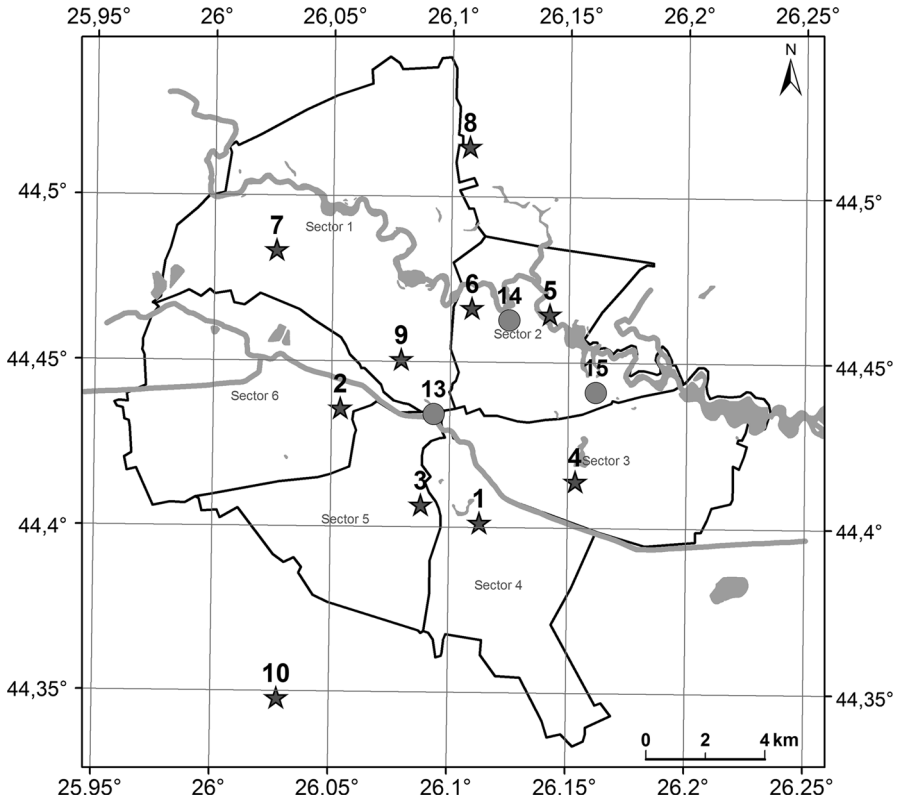
Fig. 1 Map with area under investigation—Bucharest City, Romania. Administrative sectors of Bucharest are reproduced on the map. The ten borehole sites are shown as stars labelled with numbers from 1 to 10 which correspond with those from Table 1. The three borehole sites are figured as circles (number 13–15 in Table 2) where both surface and borehole accelerometers are available

In Eq. (1), h_i and V_{Si} denote the thickness (in metres) 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, as it is defined in EUROCODE-8 (2004) and Romanian code for seismic design (2006). According to EU-ROCODE-8 (2004), the weighted mean values $\bar{V}_S$, computed for at least 30 m depth, determine 4 classes of the soil conditions:

1. Class A, rock type: $\bar{V}_S \geq 800$ m/s;
2. Class B, hard soil: $360 < \bar{V}_S < 800$ m/s;
3. Class C, intermediate soil: $180 < \bar{V}_S < 360$ m/s;
4. Class D, soft soil: $\bar{V}_S \leq 180$ m/s;

All the $V_{S\text{-}30}$ values in Table 1 belong to type C of soil after this classification, after EUROCODE-8 (2004).

The mean weighted seismic velocities for the first 6 (of 7 types) of Quaternary layers were computed for all the 10 sites in Table 1 in order to be compared with seismic velocity values obtained from previous seismic measurements and to be used as input for modelling with the widely applied program SHAKE2000. The thickness for each complex layer and for each site from Table 1 is directly measured and published by Bala et al. (2010) and

Bala ([2010](#)), and they were considered as input in SHAKE2000. They were used to compute the mean weighted shear-wave velocities in Table [1](#).

Using SHAKE2000, we compute spectral acceleration response and transfer functions for every site in which in situ measurements were performed. The acceleration response spectra correspond to the shear-wave amplifications due to the models of sedimentary layers down to (a) 50 m depth; (b) 70 m depth; and (c) 100 m depth.

4 Spectral acceleration computed by equivalent linear modelling method

The amplification of the seismic motion mainly occurs in alluvial deposits the characteristics of which (geometry and wave velocities) control the amplification process (Semblat et al. [2000](#), [2003](#)).

In the last decades, linear (viscoelastic) equivalent models were extensively used to have a simplified description, with a few parameters, of the shear modulus decrease and the hysteretic damping increase (Schnabel et al. [1972](#)). Simplified models are interesting since they may allow combined seismological/geotechnical computations to simultaneously take into account basin effects at large scales (two dimensional/three dimensional) and nonlinear local effects (Semblat [2011](#)).

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 nonlinear analysis. Extended information on these analyses is given in Kramer ([1996](#)).

To investigate seismic wave amplification in such cases, past studies have been directed to one-directional shear-wave propagation in a soil column (one-dimensional propagation), considering one motion component only (1C-polarization).

In a recent study, d'Avila et al. ([2012](#)) proposed a '1D-3C' approach, in which the three components (3C-polarization) of the incident wave are simultaneously propagated into a horizontal multilayered soil. The numerical simulations show a seismic response depending on several parameters such as polarization of seismic waves, material elastic and dynamic properties, as well as on the impedance contrast between layers and frequency content of the input motion (d'Avila et al. [2012](#)).

Theoretically speaking, truly nonlinear dynamic response analysis, in which change of mechanical property is revised in each time increment, has more potential to simulate the dynamic response of the surface ground during earthquake than equivalent linear method, because, unlike the name of 'equivalent,' equivalent linear analysis is just an approximate method. Equivalent linear method has been used, however, especially in the field of engineering practice because of several reasons. One of them is simplicity in preparing the input data and stability of numerical analysis (Miura et al. [2000](#)).

The equivalent linear method, however, has another advantage in different stand point of view. The first and very important one is deconvolution function by which incident wave to the engineering seismic base layer is computed from the earthquake record at the ground surface or any other point when multiple reflection theory is used such as SHAKE (Schnabel et al. [1972](#)).

Considering these situations, equivalent linear analysis and nonlinear analysis have a nature to compensate each other; therefore, they should be used depending on the purpose. In this paper, we are using the equivalent linear method trying to make a first assessment of the quantitative measure of the site effects due to particular geologic conditions over the Bucharest City area.

Extensive studies in which equivalent linear formulations with and without frequency-dependent moduli and damping ratios, applied on average velocity profiles down to 150 m depth, were performed by Hartzell et al. (2004). One of the conclusions is that for site classes B and C, differences are small at low-input motions (0.1–0.2 g), but become significant at higher input levels.

Since in the present study, we use an input strong motion (from a real earthquake of Mw = 6) which has a low level (under 0.1 g), the equivalent linear approach is recommended (Hartzell et al. 2004).

In our study, we apply an equivalent linear one-dimensional analysis, as implemented in the computer program SHAKE2000 (Ordóñez 2003). The *static soil properties* required in the one-dimensional ground response analysis with SHAKE2000 are maximum shear-wave velocity or maximum shear strength and unit weight. Since the analysis accounts for the nonlinear 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 (from 1 to 6). In-built shear modulus reduction curves and damping curves for specific types of layers are used in SHAKE2000 based on published geotechnical tests (Ordóñez 2003). As input data, the interval seismic velocities V_S (in m/s) as well as the natural unit weight (in kN/m^3) and thickness of each layer (in m) were used.

4.1 Strong motion applied at the base of the geologic models

With a moment magnitude of 6, the October 27, 2004 earthquake is the strongest event, which occurred after the May 1990 earthquake sequence (with two major shocks of Mw 6.9 and 6.4, respectively). It was felt countrywide. The K2 strong motion network, operated jointly by the Collaborative Research Center 461 'Strong Earthquakes' of Karlsruhe University and the National Institute for Earth Physics (NIEP), Bucharest, recorded the strong motion on 3 components. Considering only the EW horizontal component, they show variation in the PGA with amplitudes with ratio from 1 to 4 (16–65 cm/s^2) in the Bucharest city area (Bala et al. 2009a).

Although the maximum-recorded acceleration in Romania (265 cm/s^2) was close to the peak accelerations of the strong and damaging events of 1977, 1986 and 1990, the maximum intensity was 6.5 at most, calculated on the basis of Fourier Amplitude Spectra. This explains why no significant damage was registered (Bonjer et al. 2008).

The seismic event was recorded by the accelerometer network of NIEP (at surface) 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). There were 3 stations equipped with borehole K2 accelerometers at different depths which were chosen to supply the strong motion: City Hall (PRI_EW)—52 m; UTCB TEI (TEI_EW)—78 m; and INCERC (BBI_EW)—100 m (see Fig. 1; Table 2). The EW component is the strongest among the two horizontal components (EW and NS) recorded at each station (Bonjer et al. 2008), and by consequence, the EW component was chosen as the strong motion. 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.

A number of iterations are done for obtaining an error of less than 5 % in the calculations. For this purpose, 5–8 iterations are sufficient (Ordóñez 2003).

Table 2 Sites where both surface and borehole accelerometers are available in the seismic network of NCSRR (Aldea et al. 2006)

Sites equipped with borehole accelerometers				Seismic signal used for modelling	Sites where seismic signal have been used as strong motion for equivalent linear modelling
Borehole sites	Depth (m)	Average Vs (m/s)	Predominant period (whole depth) (s)		
13. City Hall	52	258	0.81	PRI_EW	Number 1–10 in Fig. 1 and Table 1 (0–50 m depth)
14. UTCB TEI	78	349	0.89	TEI_EW	Number 1–10 in Fig. 1 and Table 1 (0–70 m depth)
15. INCERC	100	364	1.54	BBI_EW	Number 5–10 in Fig. 1 and Table 1 (0–100 m depth); INCERC (0–140 m)

4.2 Spectral acceleration computed for 50 m depth models

The recorded motion of the October 27, 2004 earthquake (Mw = 6) at K2 accelerometer station PRI in Bucharest was used as seismic input motion. This accelerometer station is placed in the borehole near the City Hall site at 52 m depth. The strong motion PRI_EW (east–west component) was used for modelling as it was the highest signal of the two horizontal components. The strong motion was applied at the base of all geologic models at 50 m depth as 'inside' input motion. The geologic and geophysical models were determined by in situ seismic measurements in each of the 10 boreholes from Fig. 1 and Table 1.

The results of the equivalent linear modelling for the 10 boreholes in Bucharest are presented in the Fig. 2 as graphs of spectral acceleration. The maximum values of the spectral accelerations occur around 3 periods: $T_1 = 0.13$ s; $T_2 = 0.2$ s; $T_3 = 0.55$ s. The highest values occured at the period $T_2 = 0.2$ s, and they are between 0.22 and 0.48 g. If we consider a comparison of the values at surface, they are between 0.22 g at Romanian Shooting Federation (northern part of Bucharest) and 0.48 g (Ecologic Univ. in the central part of Bucharest).

From the distribution of the recorded PGA values in Bucarest during the October 27, 2004 earthquake (the highest value was 0.072 g at POP station in the southeastern part of the city), it is obvious that the acceleration values simulated at surface with the 50 m models is over-evaluated (Bala et al. (2009a). As a direct consequence, the spectral acceleration peaks obtained by modelling in Fig. 2 are also higher than the recorded ones. Therefore, we need to consider models with deeper depth, in order to be close to the PGA values recorded at surface.

4.3 Spectral acceleration computed for 70 m depth models

In the second stage, the recorded motion of the October 27, 2004 earthquake (Mw = 6) at accelerometer station UTCB1 in Bucharest was used as seismic input motion. This accelerometer station is placed in the borehole UTCB Tei site at 78 m depth. The strong motion TEI_EW (east–west component) was used for modelling as it was the highest signal from the two horizontal components. The strong motion was applied at the base of the geologic models constructed down to 70 m depth as 'inside' input motion. In this case, the initial geologic models of 50 m depth were completed with geologic information from nearby locations in order to obtain in each case 70 m depth geologic models.
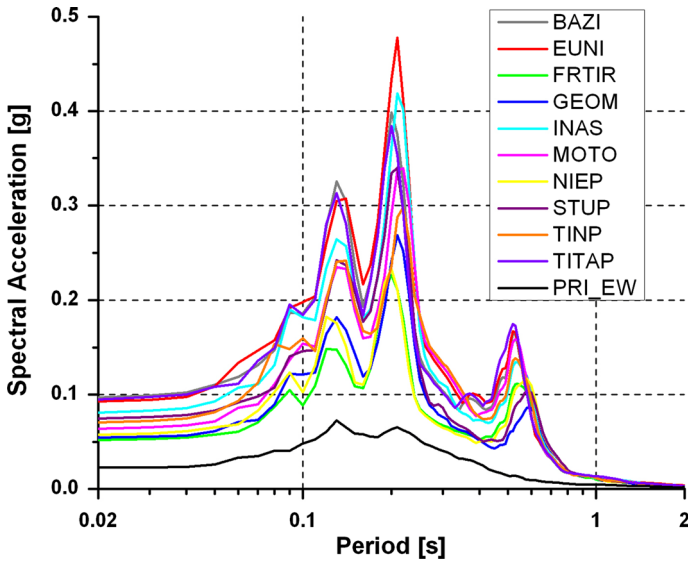
Fig. 2 Spectral acceleration response computed with the input strong motion PRI_EW for the 10 sites in Bucharest, down to 50 m depth

Spectral acceleration graphs for the 10 chosen models down to 70 m depth are presented in Fig. 3, as well as the spectral acceleration of the strong motion applied in the lower part of the figure. The spectral acceleration peak values vary from 0.15 to 0.25 g at Student Park, Geologic Museum, and F.R.Tir to 0.3 g at NIEP-Magurele in the south.

4.4 Spectral acceleration computed for 100 m depth models

In the third stage, the recorded motion of the October 27, 2004, earthquake (Mw = 6) at accelerometer station INCERC in Bucharest was used as seismic input motion BBI_EW (EW component). The strong motion BBI_EW was used for modelling as it was the deepest recorded signal in a borehole. The strong motion was applied at the base of the 6 geologic models constructed down to 100 m depth as 'inside' motion. It was also applied to a model of 140 m depth (INC_140), which resulted from in situ seismic measurements in the site INCERC (Aldea et al. 2006), see Fig. 7.

Spectral acceleration graphs for the 7 chosen models down to 100 m depth are presented in Fig. 4, as well as the spectral acceleration of the strong motion applied in the lower part of the figure. The spectral acceleration peak values vary from 0.06 to 0.11 g at Bazilescu Park and Geologic Museum. The maximum spectral acceleration of 0.11 g is lower than the values obtained in the Fig. 3 for the 70 m geologic models.
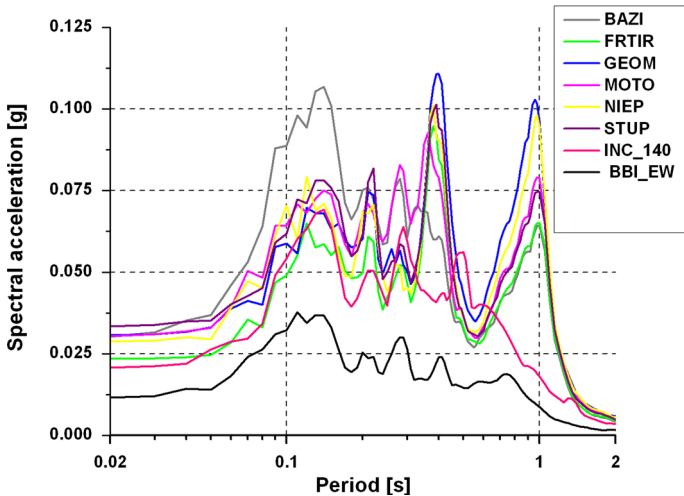
5 Calibration of the spectral acceleration computed models with a real signal recorded at surface

5.1 Calibration of the 50 m depth model with a real signal recorded at surface

In Fig. 5 the spectral acceleration of the original strong motion recorded at 52 m (PRI_EW) and the resulting spectral acceleration obtained by modelling at surface (dash
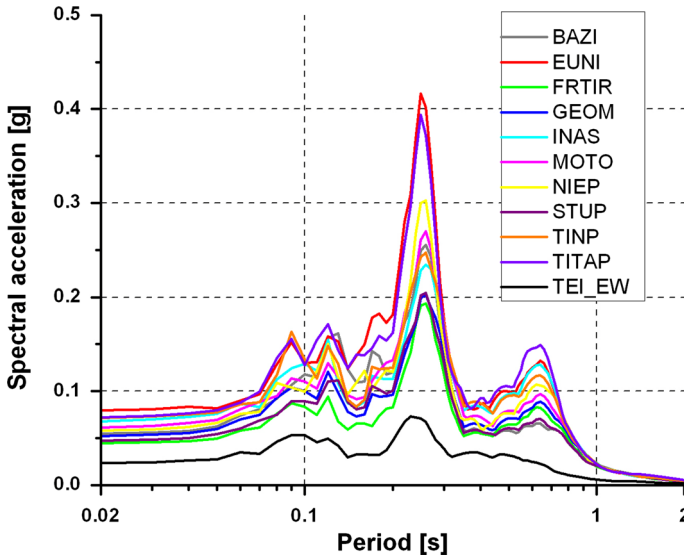
Fig. 3 Spectral acceleration response computed with the input strong motion TEI_EW for the 10 sites in Bucharest, down to 70 m depth



Fig. 4 Spectral acceleration response computed with the input strong motion BBI_EW for the 7 sites in Bucharest, down to 100 m depth

dot) are presented. The spectral acceleration of the strong motion recorded at surface in the same site (dot) is compared with the spectral acceleration obtained by modelling, and a good match is obtained, although the model has lower values in the interval 0.1–0.22 s. The peak obtained at 0.6 s in the model is due to the computing algorithm of the SHAKE2000 program which considers an enhanced natural period for a model with bedrock at 50 m depth, which is not the case. This peak cannot be observed on the recorded signal.
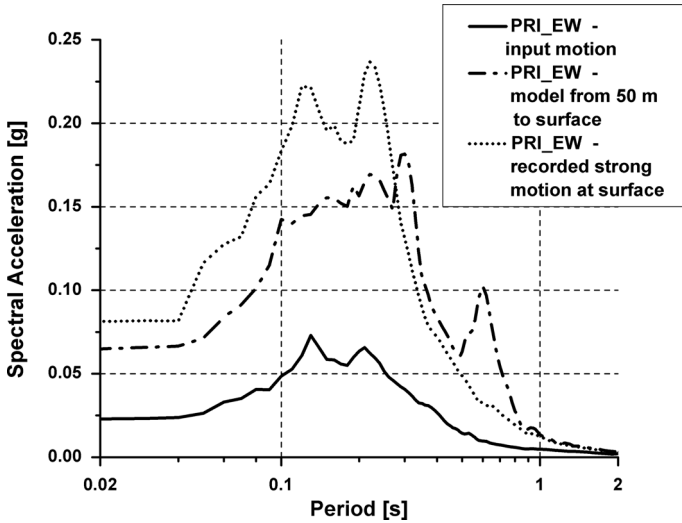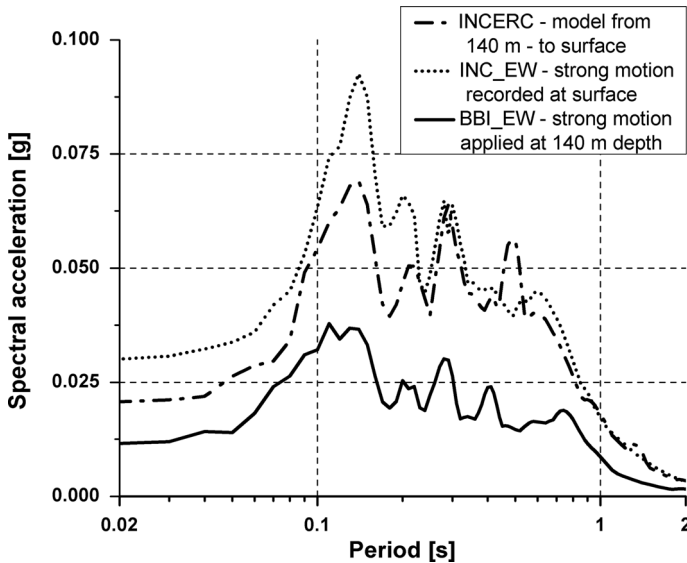
Fig. 5 Spectral acceleration calibration of the depth model City Hall (0–50 m), PRI_EW strong motion, with the seismic signal recorded at surface in the same place; *line* strong motion applied to the model; *line-dot* spectral acceleration model computed at surface; *dot* spectral acceleration of the seismic signal recorded at surface
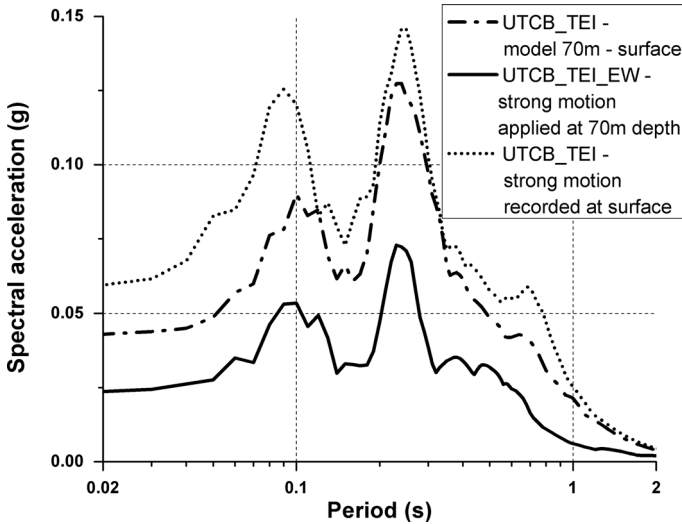
Fig. 6 Spectral acceleration calibration of the depth model UTCB TEI (0–70 m), TEI_EW strong motion, with the signal recorded at surface in the same place; *line* strong motion applied to the model; *line-dot* spectral acceleration model computed at surface; *dot* spectral acceleration of the signal recorded at surface

5.2 Calibration of the 70 m model with a real signal recorded at surface

In Fig. 6, the spectral acceleration of the original strong motion recorded at 78 m (TEI_EW) and the resulting spectral acceleration obtained by modelling at surface (dash

Fig. 7 Spectral acceleration calibration of the model INCERC (0–100 m), BBI_EW 100-m-strong motion, with the signal recorded at surface in the same place; *line* strong motion applied to the model; *line-dot* spectral acceleration model at surface; *dot* spectral acceleration recorded at surface

dot) are presented. The spectral acceleration of the strong motion recorded at surface in the same site (dot) is compared with the spectral acceleration obtained by modelling, and a very good match is obtained, although the second has lower values especially around the first peak at 0.1 s.

5.3 Calibration of the 100 m model with a real signal recorded at surface

In Fig. 7, the spectral acceleration of the original strong motion recorded at 100 m (BBI_EW) and the resulting spectral acceleration obtained by modelling at surface are presented.

The spectral acceleration of the strong motion recorded at surface in the same site is compared with the spectral acceleration obtained by modelling, and a good match is obtained, although the second has lower values especially around the first peak at 0.15 s.

The spectral acceleration graphs in Fig. 7 have two peaks: one at 0.15 s and the second at 0.3 s, at the same periods as the spectral acceleration of the original strong motion. The absolute value reaches 0.090 g at 0.15 s, which means an amplification of 3 times of the original signal through the shallow sedimentary layers. The spectral acceleration of the model presents also a peak at 0.5 s which cannot be observed on the recorded signal.

6 Discussion of the main results

Spectral acceleration peaks in Figs. 2, 3 and 4 appear in general at the same periods as the peaks of the input motion. However, the spectral acceleration level shows important variation across the city due to the particular one-dimensional geologic models adopted: the number of layers and their thickness, as well as the shear-wave seismic velocities

measured for each layer. So the spectral acceleration range is 0.225–0. 475 g for 50 m depth models and 0.2–0.4 g for 70 m models. For 100 m depth models, spectral acceleration has a more complex variation between 0.06 and 0.11 g and displays several peaks in the interval 0.1–1 s. These peaks appear as a result of lateral variation in geology and not due to directivity, as it was shown that due to the geometry of the source-site path, the seismic waves arrive almost on a vertical direction in the underground of Bucharest. Their frequency content depends almost entirely on the frequency content of the seismic signal applied at the bottom of the model.

Calibrations have been performed for models with 3 depth values: 50, 70 and 100 m. A comparison of the spectral acceleration of the model with the spectral acceleration of the real signal recorded at surface displays a good match (Figs. 5, 6 and 7).

However, for the model of 50 m depth some important nonlinear effects appear (the amplitude is too small and there is a frequency/period shift). It is important to note that these nonlinear effects appear when the shear-wave velocity of the geologic layers is too small or the shear modulus and damping curves are underestimated. In this particular case, it is probably a combination of these two data sets.

A comparison with the spectral acceleration resulted from EC8 is given in Fig. 8 for a generic earthquake type 2, with acceleration of 0.1 g and soil type C, as in our specific data. Although these values are close to the applied values in our example, the spectral acceleration of the model is only half of the value of that given in EC8 for an earthquake type 2.
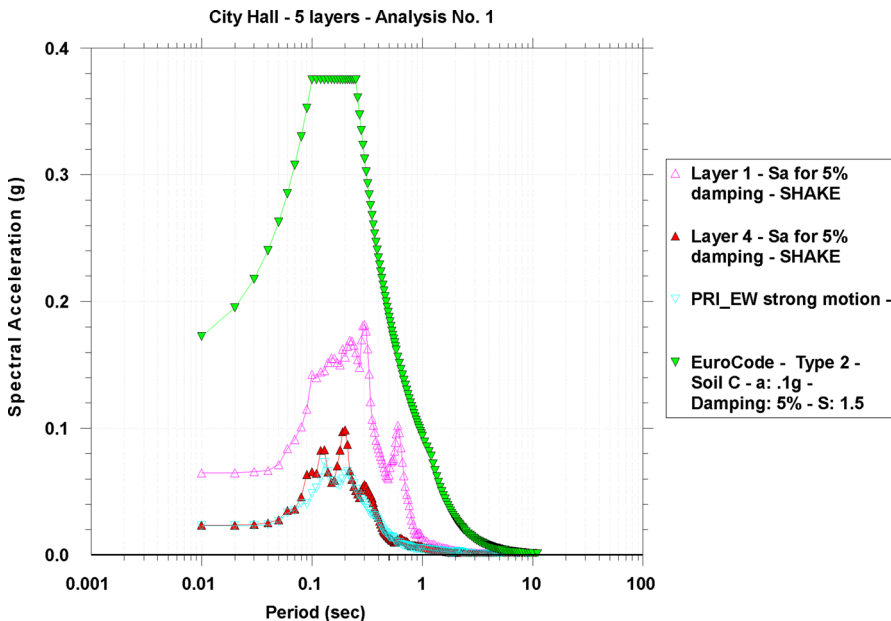
Fig. 8 Spectral acceleration of the depth model City Hall (0–50 m) at surface-Layer 1 (*purple triangles*) in comparison with the SA resulted from EC8 (a generic earthquake type 2, with acceleration of 0.1 g and soil type C, as in our specific data)—*green triangles*. The input motion is applied at the lower interface of the Layer 4 (*red triangles*) that stands for the bottom layer of the model

The match is better when we consider deeper models of 100 m depth, as the difference between the spectral acceleration resulted from modelling and the spectral acceleration of the signal recorded at surface is minor.

The spectral acceleration–computed models, for the depths interval of 50, 70 and 100 m, do not reach the spectral acceleration of the strong motion recorded at surface. There are probably other factors, which are not accounted in our analysis, responsible for the increasing values of spectral acceleration recorded at surface. Among them might be real depth of the EB, which is obviously deeper than the depths considered here; values of the shear modulus reduction curves and damping curves for specific types of layers which might be underestimated in our analysis; the water saturation in the porous layers; and the type and the level of the strong motion applied.

The nonlinear constitutive parameters might have also a strong influence on the results. Approximately 250 samples were gathered from the first 10 drill sites, as shown in Fig. 1, during the NATO SfP Project 981882. These samples were mostly not disturbed (as they were recovered from the tube of the drilling rig) and partly disturbed.

The geotechnical laboratory analysis consists in the following parts: geological identification of the sample, identification of the sample after the ternary diagram, percentage of composition, triaxial (dynamic) test and resonant column tests. Cyclic loading tests were performed on cohesionless soil samples collected from 4 sites (drillings) and also on cohesion soil samples collected from 8 sites during the NATO SfP Project 981882.

Bala et al. (2013) presented the results of the geotechnical laboratory analysis for uncohesive soils (4 sample cores) and for cohesive soils (8 sample cores) in Bucharest. They were compared with analytical curves and a good match is obtained for G/G_{max} curves, which are positioned between the lower bound and the upper bound curves. Damping ratio curves are also found to have some variability, between the lower bound and the upper bound curves which are implemented in the program SHAKE2000.

However, due to the fact that the nonlinear constitutive parameters were measured only on a few samples (not for all the 10 drilling points) and also because they are characterizing only the depth interval down to 50 m depth, the curves implemented in the program SHAKE2000 were used instead. They were adopted according to the geologic composition of each layer, as well as the depth of the layer in the geologic profile, contributing to the results of the modelling.

The present work should be completed with an analysis of the spectral acceleration modelling with shear modulus and damping ratio curves obtained from geotechnical measurements in order to have all the geotechnical data as close to real case as possible.

Multiplying the sites in which the equivalent linear method is applied will give the possibility of quantitative mapping of the seismic site response, which will have a major impact on the local hazard in Bucharest area.

7 Conclusions

1. The spectral acceleration graphs in Figs. 2, 3 and 4, corresponding to the three depth models, show that the computed models peak at the same periods as the spectral acceleration of the original strong motion applied at the base of the model. The absolute values of the peaks are almost three times higher than the original signal, suffering a strong amplification of seismic signal through the shallow sedimentary layers in the geological model.

2. A strong peak which appeared at higher periods, between 0.5 and 0.6 s (Figs. 2, 3) and 1 s (Fig. 4), is considered as introduced by the computer algorithm of the SHAKE2000 program. It represents the dominant period for a package of sedimentary layers with a depth of the model adopted. However, due to the fact that the depth of the model does not coincide with the EB in our examples, the real motion recorded at surface does not show this peak (Figs. 6, 7). This demonstrates that this peak is a fake and should not be considered for further analysis.

3. Calibration has been performed for models with three depth values: 50, 70 and 100 m. A comparison of the spectral acceleration of the model with the spectral acceleration of the real signal recorded at surface display a good match (Figs. 5, 6, 7). The match is better when we consider deeper models of 100 m depth. However, in the three figures the spectral acceleration–computed models, for the depths interval of 50, 70 and 100 m, do not reach the spectral acceleration of the strong motion recorded at surface, suggesting that there are some other causes that contribute to the site-effects modelling, besides the factor considered here.

4. The above conclusions are a good argument for the observation that the EB in Bucharest should be deeper than 100 m and should be placed between 200 and 500 m depth. Other geological observations placed the bedrock at 500–1,500 m depth in the Bucharest area, coinciding with the upper interface of the Cretaceous limestone with shear-wave seismic velocity of about 2,900–3,000 m/s (Bala 2010).

5. The quantitative aspect of site effects in the Bucharest area is very important, in a big city threatened by large earthquakes with magnitudes over Mw = 7. The importance of the site effects have been discussed several times, but without a proper quantitative treating like in the present paper.

Moreover, the modelling in this paper is performed with real input parameters, all measured in the field, and it brings new insights of the spectral acceleration in Bucharest city. These models were calibrated with surface recordings performed in the same sites, and the comparison in Sect. 4 suggested that the method provide reliable results, results which are closer to reality if we consider deeper models. The method should be extended to the rest of the city in order to provide a real map of the site effects in Bucharest.

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