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EARTH PHYSICS

MODELLING OF SEISMIC SITE AMPLIFICATION BASED ON IN SITU GEOPHYSICAL MEASUREMENTS IN BUCHAREST, ROMANIA

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Abstract. 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, density for each sedimentary layer is set up.

Results obtained by the down-hole method in the new boreholes drilled in Bucharest City as well as from laboratory measurements are used as input data in the program SHAKE2000. Spectral acceleration response and peak acceleration in depth are computed 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; c) 100 m depth. A comparison with a real signal recorded at surface is made in order to calibrate the models used in the equivalent-liniar evaluation of the seismic site response.

Key words: seismic site amplification; borehole seismic measurements; modeling by equivalent-linear approach.

1. GEOLOGIC BACKGROUND OF THE BUCHAREST CITY AREA

For an earthquake endangered region, the city area of Bucharest presents quite special geological conditions: the absence of hard bedrock down to Cretaceous upper limit at 500–1500 m depth (Lacatusu *et al.*, 2007, [13]); an alternation of up to 300 m thick Quaternary sand and clay layers near surface; among the sand and clay layers three main porous aquifer systems. Strong lateral heterogeneities and important vertical thickness variations of these soft soil deposits complicate the geologic structure.

1.1. CLASSIFICATION OF THE QUATERNARY DEPOSITS

A first classification on the geological and lithological description of the Quaternary deposits in the Bucharest area is found in (Liteanu, 1952, [14]). This classification of 7 main sedimentary complexes (beginning from the surface to depth) is accepted until today (in Bala *et al.*, 2006, [2]; Bala *et al.*, 2009c, [5]) and was considerably improved in recent studies (Ciugudean-Toma and Stefanescu, 2006, [9]). This classification comprises the following names and general characteristics:

Layer 1: ***Anthropogenic backfill and soil***, with a thickness varying between 3–10 m.

Layer 2: The *Upper clayey-sandy complex*, represent Holocene deposits of Loess, sandy clays and sands. The thickness of this complex varies between 2 and 5 m in the "Dambovita-Colentina inter-fluvial domain", 10 and 16 m in the northern and southern Plaines (Baneasa-Pantelimon and Cotroceni-Vacaresti) and 3 and 6 m in the river meadows.

Layer 3: The ***Colentina gravel complex*** bearing the *Colentina-aquifer*, is a layer containing gravels and sands with varying grain size distribution. The thickness is variable, between 1–20 m, lacking in the western part of Bucharest.

Layer 4: The ***Intermediate clay layer*** contains up to 80% hard consolidated clay and calcareous concretions with intercalated thin sand and silt lenses. The thickness of this layer varies between 0 and 25 m.

Layer 5: The ***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: The ***Lacustrine complex*,** composed by a variation of limy marled clay and fine sands, the grain size < 0,005 mm consisting about 86%. The upper face of the complex lies at 20-50 m depth, but 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 descents northward.

Layer 7: The ***Fratesti complex*** or *Lower gravel 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), continuous present in the whole area of Bucharest, dips northward, its upper surface lying at about 75 m depth in the southern part of Bucharest and at about 190 m depth in the North.

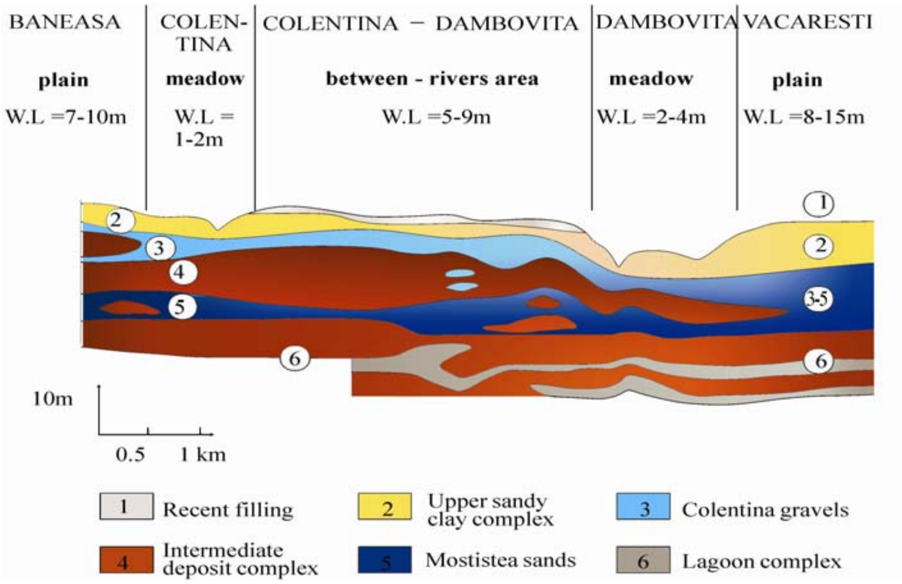

Fig. 1 – Geomorhpologic section, N-S direction, with principal shallow sedimentary layers. After Cigudean and Stefanescu, 2006.

2. SEISMIC MEASUREMENTS PERFORMED IN BUCHAREST CITY

The latest results in the shearwave velocity measurements were obtained in the frame of the NATO SfP Project 981882 (2006–2009), reported by Bala *et al.* (2007, [3]) and the Romanian project 31–038 (2007–2010), reported by Bala *et al.* (2009b, [5]); Bala *et al.* (2011, [8]). 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. 2).

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

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

In equation (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, as it is defined in EUROCODE8 (2004) and Romanian code for seismic design (2006). According to EUROCODE8 (2004, [11]), 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 $\boldsymbol{V_{S\text{-}30}}$ values in Table 1 belong to type C of soil after this classification, after EUROCODE8 (2004).

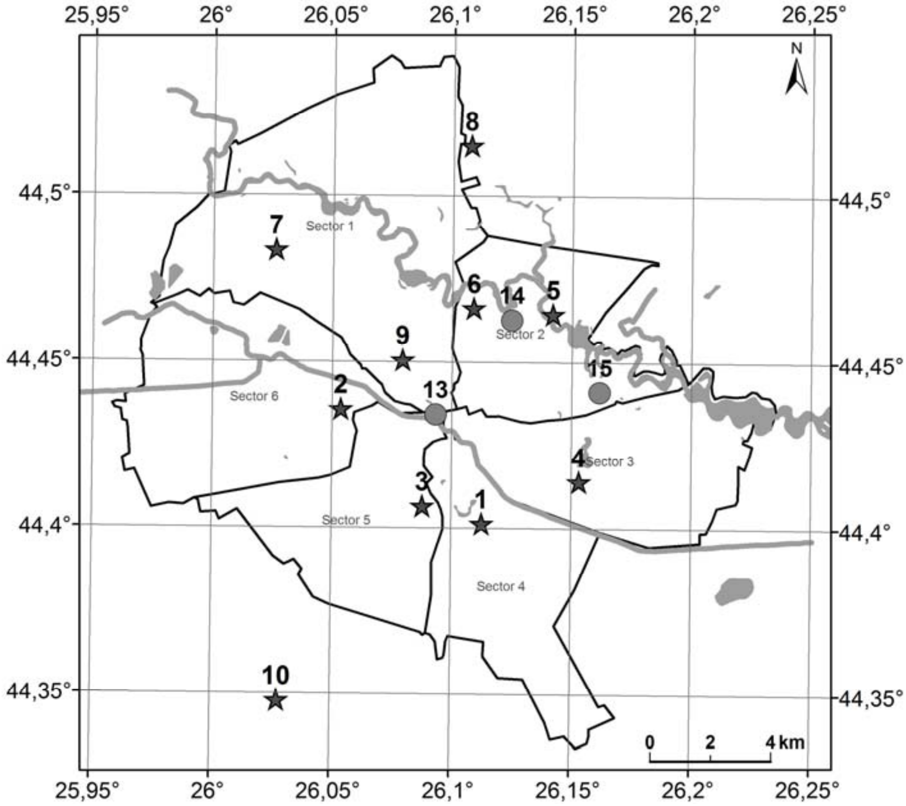

Fig. 2 – Map with area under investigation – Bucharest City, Romania. Administrative sectors of Bucharest are reproduced on the map. The ten borehole sites are shown as stars labelled with numbers from 1 to 10 which correspond with those from Table 1. The 3 borehole sites are figured as circles (number 13–15 in Table 2) where both surface and borehole accelerometers are available.

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. In the present paper we compute spectral acceleration response and transfer functions using SHAKE2000 program 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; c) 100 m depth.

Table 1

Mean weighted seismic velocities for the first 6 (of 7 types) of Quaternary layers in 10 boreholes in Bucharest City. Description of the geologic layers is given in Chapter 1 (after Ciugudean-Toma and Stefanescu, 2006)

Geologic stratum type	**1**		**2**		**3**		**4**		**5**		**6**		
Borehole site/symbol	**Mean weighted seismic velocities [m/s]**												
	Vp	**Vs**	**Vp**	**Vs**	**Vp**	**Vs**	**Vp**	**Vs**	**Vp**	**Vs**	**Vp**	**Vs**	**V_{S30}**
1.Tineret Park **TINP**	**180**	**140**	**570**	**220**	**856**	**299**	**---**	**--**	**1666**	**398**	**---**	**---**	***263***
2.Ecology University **EUNI**	**300**	**120**	**1180**	**220**	**1250**	**241**	**1610**	**354**	**1850**	**390**	**2042**	**401**	***286***
3.Astronomy Institute **INAS**	**200**	**120**	**914**	**260**	**1200**	**330**	**1440**	**350**	**1900**	**390**	**2124**	**433**	***283***
4.Titan2 Park **TITAP**	**290**	**160**	**800**	**250**	**800**	**250**	**980**	**350**	**1576**	**381**	**1850**	**450**	***299***
5.Motodrom Park **MOTO**	**650**	**200**	**650**	**200**	**1320**	**320**	**1827**	**393**	**1980**	**410**	**2050**	**410**	***288***
6.Student Park **STUP**	**490**	**210**	**490**	**210**	**1361**	**342**	**1570**	**370**	**1607**	**375**	**1820**	**400**	***295***
7.Bazilescu Park **BAZI**	**500**	**160**	**500**	**160**	**1484**	**317**	**1850**	**390**	**2103**	**408**	**---**	**---**	***294***
8.Romanian ShootingFed. **FRTIR**	**670**	**210**	**1440**	**330**	**1440**	**350**	**1718**	**400**	**1900**	**400**	**---**	**---**	***327***
9.Geologic Museum **GEOM**	**340**	**180**	**1250**	**310**	**1511**	**322**	**1935**	**376**	**1950**	**380**	**---**	**---**	***320***
10. *NIEP site* **NIEP**	**370**	**250**	**1710**	**350**	**1710**	**350**	**1810**	**320**	**1739**	**337**	**2090**	**410**	***326***
All sites.	***325***	***169***	***854***	***252***	***1243***	***320***	***1530***	***367***	***1832***	***386***	***2005***	***417***	

3. SPECTRAL ACCELERATION COMPUTED BY EQUIVALENT LINEAR MODELLING METHOD

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) [12]. Here we apply an equivalent linear one-dimensional analysis, as implemented in the computer program SHAKE2000 (Ordónez, 2003) [16]. 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.

In-built shear modulus reduction curves and damping curves for specific types of layers are used in SHAKE2000 based on published geotechnical tests (Ordónez, 2003) [16]. 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.

3.1. STRONG MOTION APPLIED AT THE BASE OF THE GEOLOGIC MODELS

The earthquake of 27.10.2004 (M_w = 6) was one of the best documented earthquakes in Romania by a great number of records, in most cases being available all 3 components (one vertical and two horizontal). 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) [1].

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; INCERC (BBI_EW) – 100 m (Fig. 2 and Table 2). Usually the EW component is the strongest among the 2 horizontal recordings at each station and was used as the horizontal component.

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. The spectral acceleration of the 3 strong motions which were chosen for modelling are presented in Fig. 3.

The signal content is between 0.08 and 1 sec for all 3 signals, the deepest one displaying more peaks distributed in the interval 0.1–1 s. While the amplitude for this signal is about 0.038 g, the amplitudes of the signals recorded at 70 m and 50 m depth is about 0.075 g, almost twice as much as the amplitude of the deepest signal.

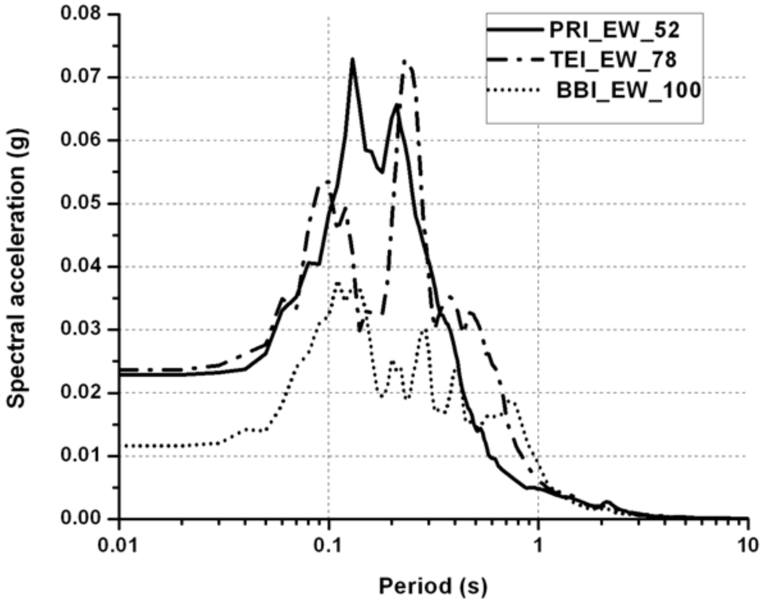

Fig. 3 – Spectral acceleration of the 3 strong motions chosen for modelling: PRI_EW – 52 m; TEI_EW – 78 m; BBI_EW – 100 m.

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 m	258	0.81	PRI_EW	Number 1–10 in Fig. 1 and Table 1 (0–50 m depth)
14. UTCB TEI	78 m	349	0.89	TEI_EW	Number 1–10 in Fig. 1 and Table 1 (0–70 m depth)
15. INCERC	100 m	364	1.54	BBI_EW	Number 5–10 in Fig. 1 and Table 1 (0–100 m depth) ; INCERC (0–140 m).

3.2. SPECTRAL ACCELERATION COMPUTED FOR 50 m DEPTH MODELS

The recorded motion of the 27.10.2004 earthquake (M_w = 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. 2 and Table 1.

The results of the equivalent-linear modeling with SHAKE2000 program for the 10 boreholes are presented in the Fig. 4 as graphs of spectral acceleration. In Fig. 4 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 g 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), after Bala *et al.* (2010) [6].

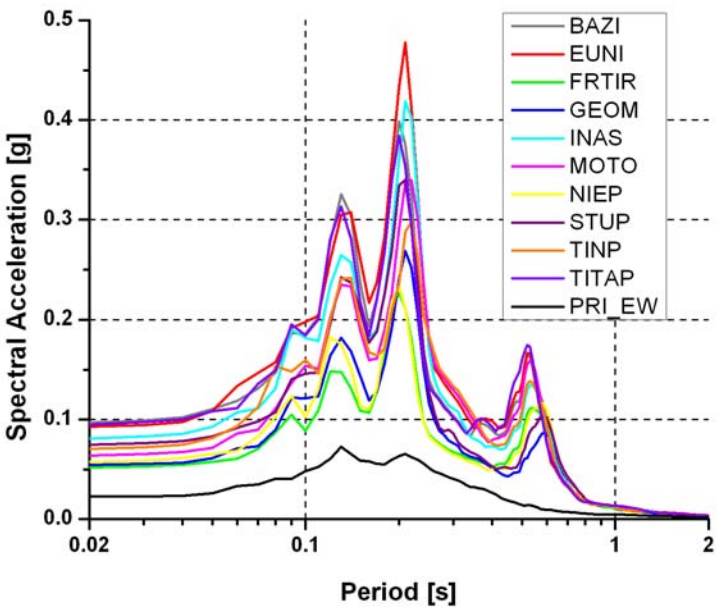

Fig. 4 – Spectral acceleration response computed with the input strong motion PRI_EW for the 10 sites in Bucharest, down to 50 m depth.

The values of acceleration at surface are presented in the Fig. 5 and they are between 0.055–0.080 g for the first 7 out of the 10 boreholes. For the last 3 sites values as large s 0.08–0.095 g resulted from modeling (Ecologic Univ.; Titan 2 Park; Bazilescu Park). These high values are greatly influenced by the thickness of the Quaternary layers 1 and 2 from the surface and also by the physical and dynamic characteristics of all layers.

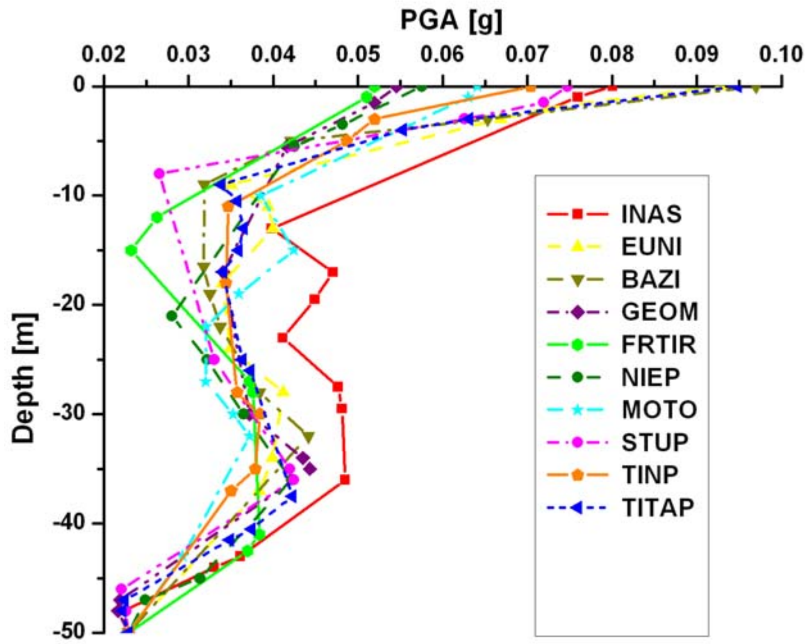

Fig. 5 – PGA variation with depth as result from equivalent-linear modelling in the 10 boreholes in Bucharest, down to 50 m depth.

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 south-eastern part of the city – Bala *et al.* (2009a) [4], it is obvious that the acceleration values simulated at surface with the 50 m models is over-evaluated. As a direct consequence the spectral acceleration peaks obtained by modelling in Fig. 4 are also higher than the recorded ones. Therefore we need to consider models with beeper depth, in order to be closet o the PGA values recorded at surface.

3.3. SPECTRAL ACCELERATION COMPUTED FOR 70 m DEPTH MODELS

In the second stage the recorded motion of the 27.10.2004 earthquake (M_w = 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 information from nearby locations in order to obtain in each case 70 m depth geologic models.

Spectral acceleration graphs for the 10 chosen models down to 70 m depth are presented in Fig. 6, as well as the spectral acceleration of the strong motion applied in the lower part of the figure. The spectral acceleration peaks values varies from 0.15–0.25 g at Student Park, Geologic Museum and F.R.Tir to 0.3 g at NIEP-Magurele in the south. Maximum values of 0.4 g are present at Ecologic Univ. and Titan 2 Park, lower than the values obtained in the Fig. 4 for the 50 m geologic models.

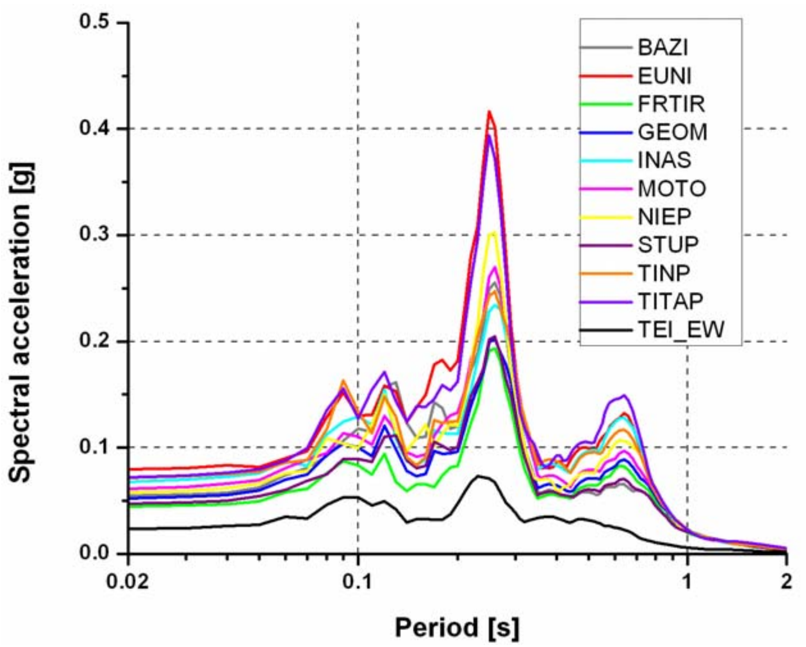

Fig. 6 – Spectral acceleration response computed with the input strong motion TEI_EW for the 10 sites in Bucharest, down to 70 m depth.

The variation of peak acceleration in the depth is presented in the Fig. 7 for the 10 sites and they are between 0.023 g (at 70 m depth) and it can reach 0.045–0.08 g at surface, lower than the maximum values presented in the Fig. 5 for the 50 m geologic models.

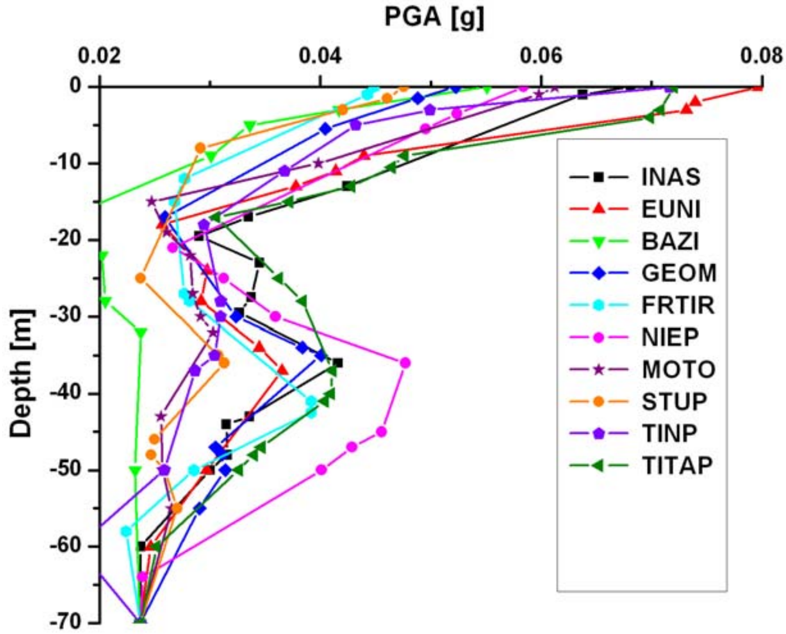

Fig. 7 – PGA variation with depth as result from equivalent-linear modelling in the 10 sites in Bucharest, down to 70 m depth.

3.4. SPECTRAL ACCELERATION COMPUTED FOR 100 m DEPTH MODELS

In the third stage the recorded motion of the 27.10.2004 earthquake (M_w = 6) at accelerometer station INCERC in Bucharest was used as seismic input motion BBI_EW (EW component). This seismic station is placed in the borehole at INCERC site at 100 m depth. 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) [1].

Spectral acceleration graphs for the 7 chosen models down to 100 m depth are presented in Fig. 8, as well as the spectral acceleration of the strong motion applied in the lower part of Fig. 8. The spectral acceleration peaks values varies from 0.06–0.11 g at Bazilescu Park and Geologic Museum. The maximum spectral acceleration of 0.11 g are lower than the values obtained in the Fig. 6 for the 70 m geologic models.

The variation of peak acceleration *versus* depth in Fig. 9 for the 7 sites reveal a a domain between 0.01–0.035 g for the depth between 100 m and surface, which is half of the values in Fig. 7 found for the 70 m depth models.

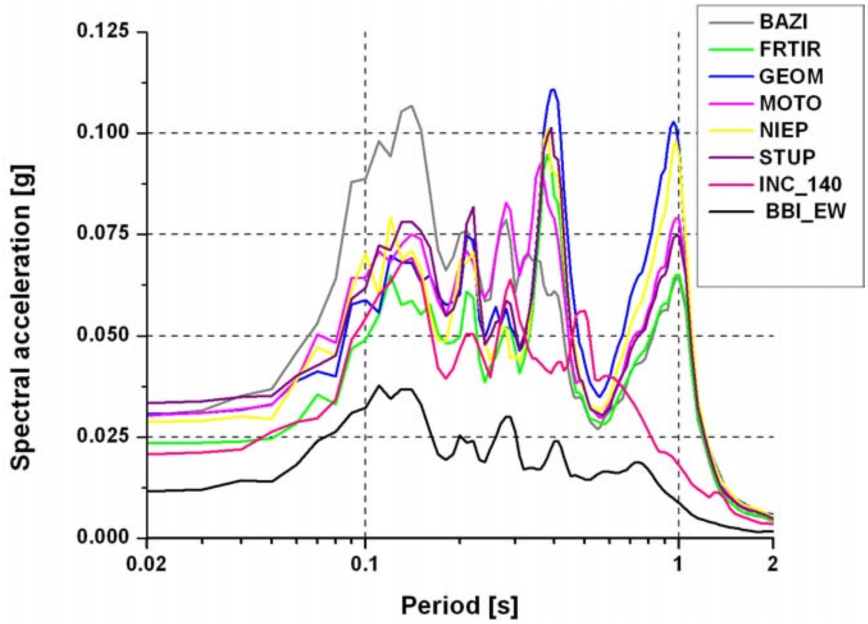

Fig. 8 – Spectral acceleration response computed with the input strong motion BBI_EW for the 7 sites in Bucharest, down to 100 m depth.

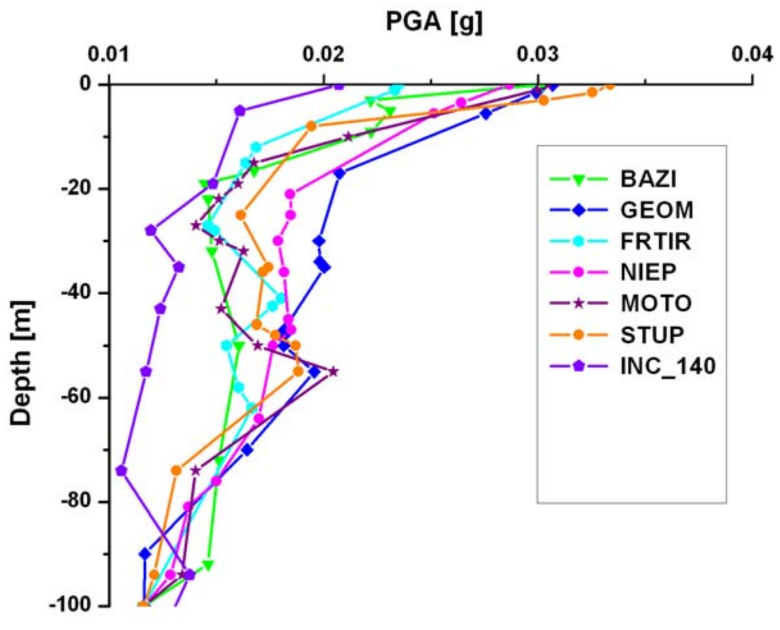

Fig. 9 – PGA variation with depth as result from equivalent-linear modelling in the 7 sites in Bucharest, down to 100 m depth.

4. CALIBRATION OF THE SPECTRAL ACCELERATION COMPUTED MODELS WITH A REAL SIGNAL RECORDED AT SURFACE

4.1. CALIBRATION OF THE 50 m DEPTH MODEL WITH A REAL SIGNAL RECORDED AT SURFACE

In Fig. 10 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 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 can not be observed on the recorded signal.

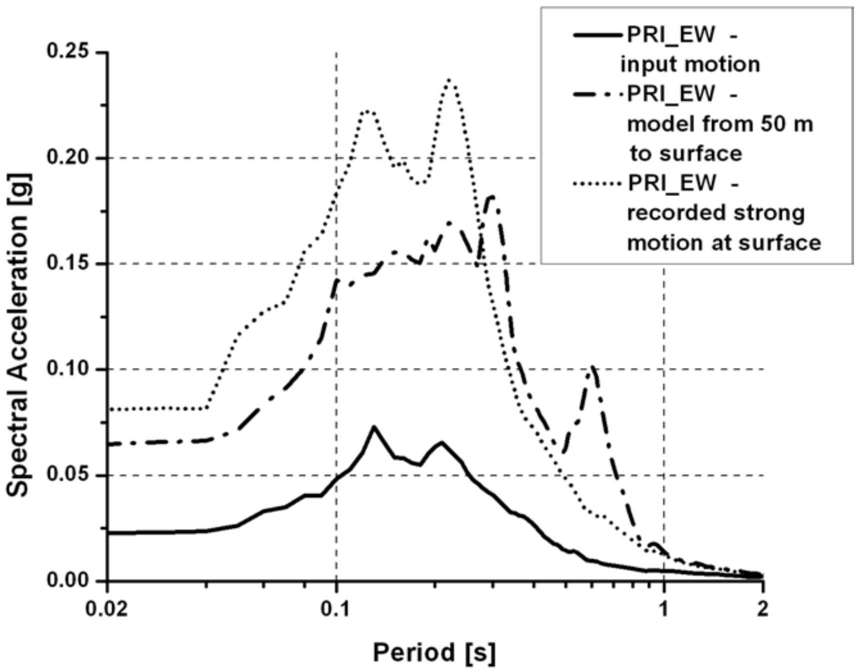

Fig. 10 – Spectral acceleration calibration of the depth model City Hall (0–50 m), PRI_EW strong motion, with the seismic signal recorded at surface in the same place; line – strong motion applied to the model; line-dot – spectral acceleration model computed at surface; dot – spectral acceleration of the seismic signal recorded at surface.

4.2. CALIBRATION OF THE 70 m MODEL WITH A REAL SIGNAL RECORDED AT SURFACE

In Fig. 11 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 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.

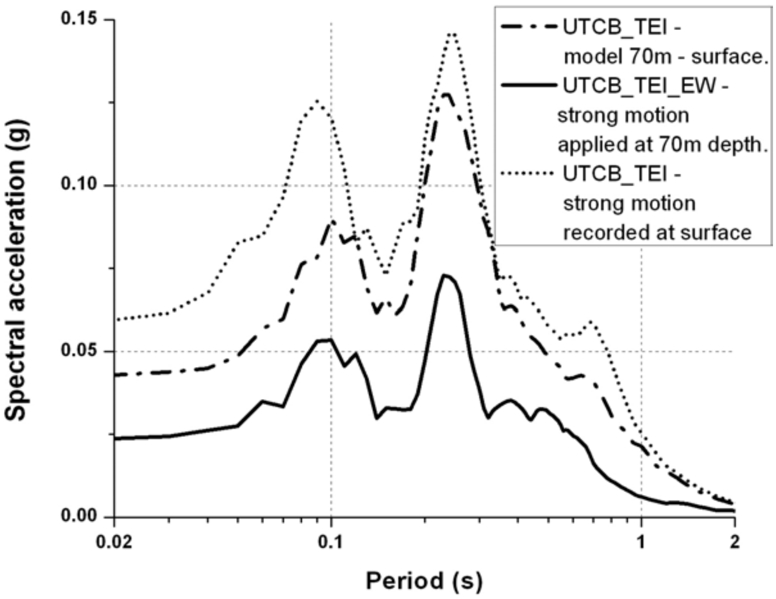

Fig. 11 – Spectral acceleration calibration of the depth model UTCB TEI (0–70 m), TEI_EW strong motion, with the signal recorded at surface in the same place; line – strong motion applied to the model; line-dot – spectral acceleration model computed at surface; dot – spectral acceleration of the signal recorded at surface.

4.3. CALIBRATION OF THE 100 m MODEL WITH A REAL SIGNAL RECORDED AT SURFACE

In Fig. 12 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.

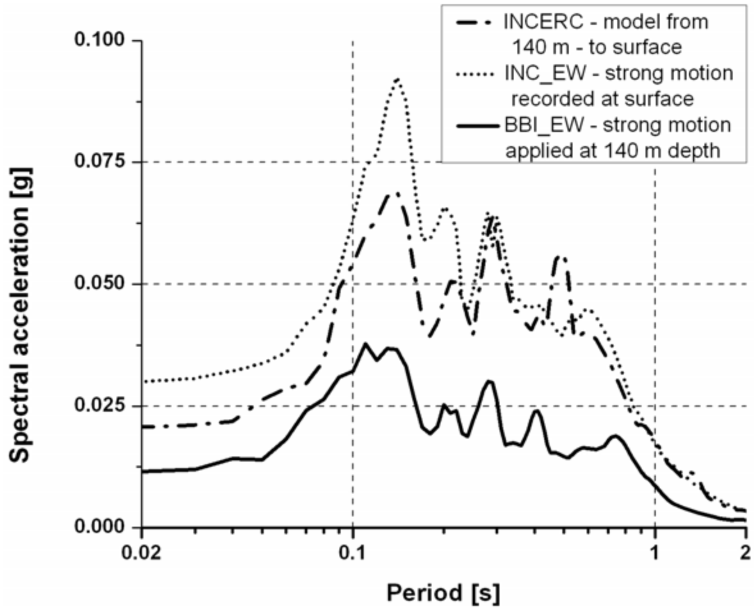

Fig. 12 – Spectral acceleration calibration of the model INCERC (0–100 m), BBI_EW 100 m strong motion, with the signal recorded at surface in the same place; line – strong motion applied to the model; line-dot – spectral acceleration model at surface; dot – spectral acceleration recorded at surface.

The spectral acceleration graphs in Fig. 12 have 2 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 can not be observed on the recorded signal.

5. CONCLUSIONS

1. The spectral acceleration graphs in Figs. 4, 6 and 8, corresponding to the 3 depth models, show that the computed models peaks 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 3 times higher than the original signal, suffering a strong amplification of seismic signal through the shallow sedimentary layers in the geological model.

2. The acceleration graphs computed in the depth in Figs. 5, 7 and 9 show some variations between the bottom depth of the models and the level of 20–25 m. A sharp increase of the acceleration occurs from this level to the surface.

From the distribution of the recorded PGA values in Bucharest during the October 27, 2004 earthquake (the highest value was 0.06 g at BAP station in the central part of the city) it is obvious that the acceleration values simulated with the 50 m depth models is overevaluated; therefore we need to consider models with at least 70–100 m depth.

3. A strong peak which appeared at higher periods, between 0.5–0.6 s (Fig. 4 and Fig. 6) and 1 s (Fig. 8) 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 engineering bedrock in our examples, the real motion recorded at surface does not show this peak (Figs. 11 and 12). This demonstrates that this peak is a fake and should not be considered for further analysis.

4. Calibration has been performed for models with 3 depth values: 50 m; 70 m; 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. 10, 11 and 12). The match is better when we consider deeper models of 100 m depth. However in Figs. 10–12 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 the equivalent linear modelling, responsible for the increasing values of spectral acceleration recorded at surface. Among them might be: real depth of the engineering bedrock, which is obviously deeper than the depth 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; the type and the level of the strong motion applied.

5. The above conclusions are a good argument for the observation that the engineering bedrock in Bucharest should be deeper than 100 m and should be placed between 200–500 m depth. Other geological observations placed the bedrock at 500–1000 m depth in the Bucharest area, coinciding with the upper interface of the Cretaceous limestone with sharewave seismic velocity of about 2900–3000 m/s (Bala, 2010) [7].

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