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Modelling of Seismic Site Amplification based on *in situ* Borehole Measurements in Bucharest, Romania

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Extended Abstract

Within the NATO Science for Peace Project 981882 *"Site-effect analyses for the earthquake-endangered metropolis Bucharest, Romania"* we obtained a unique, homogeneous dataset of seismic, soil-mechanic and elasto-dynamic parameters. Ten 50 m deep boreholes were drilled in the metropolitan area of Bucharest in order to obtain cores for dynamic tests and vertical seismic profiles for an updated microzonation map related to earthquake wave amplification. The boreholes were placed near former or existing seismic station sites to allow us a direct comparison and calibration of the borehole data with actual seismological measurements. A database was assembled which contains P- and S-wave velocity, density, geotechnical parameters measured at rock samples and geological characteristics for each sedimentary layer.

Bucharest, the capital of Romania, with more than 2 million inhabitants, is considered, after Istanbul, the second-most earthquake-endangered metropolis in Europe. It is identified as a natural disaster hotspot by a recent global study of the World Bank and the Columbia University. Four major earthquakes with moment-magnitudes between 6.9 and 7.7 hit Bucharest in the last 65 years. The most recent destructive earthquake of 4 March 1977, with a moment magnitude of 7.4, caused about 1.500 casualties in the capital alone. All disastrous earthquakes are generated within a small epicentral area - the Vrancea region- about 150 -160 km north-east of Bucharest. Thick unconsolidated sedimentary layers in the area of Bucharest amplify the arriving seismic shear-waves causing severe destruction. Thus, disaster prevention and mitigation of earthquake effects is an issue of highest priority for Bucharest.
The main purpose of the **NATO SfP Project 981882** was to obtain a unique, homogeneous dataset of soil-mechanic and elasto-dynamic parameters of the subsurface of Bucharest from 10 new boreholes to model the so-called seismic site responses.

1. Results of the down-hole seismic measurements

The mean weighted seismic velocities for the first 6 (of 7 types) of Quaternary layers were computed for all the 10 sites, 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.
Using SHAKE2000 we computed spectral acceleration response and transfer functions obtained from the *in situ* measurements. The acceleration response spectra correspond to the shear-wave amplifications due to the sedimentary layers from 50 m depth (maximum depth) up to the surface.

Table 1. Mean weighted seismic velocities for the first 6 (of 7 types) of Quaternary layers in 10 boreholes in Bucharest City. For a description of the layers see Ciugudean-Toma and Stefanescu (2006).

	Geologic stratum type	1		2		3		4		5		6			
		Mean weighted seismic velocities [m/s]													
		Vp	Vs	Vp	Vs	Vp	Vs	Vp	Vs	Vp	Vs	Vp	Vs	V_{S-30}	V_{S-50}
1.	Tineret Park	180	140	570	220	856	299	---	--	1666	398	---	---	263	304
2.	Ecology Univ.	300	120	1180	220	1250	241	1610	354	1850	390	2042	401	286	326
3.	Astronomy Institute	200	120	914	260	1200	330	1440	350	1900	390	2124	433	283	320
4.	Titan2 Park	290	160	800	250	800	250	980	350	1576	381	1850	450	299	341
5.	Motodrom Park	650	200	650	200	1320	320	1827	393	1980	410	2050	410	288	327
6.	Student Park	490	210	490	210	1361	342	1570	370	1607	375	1820	400	295	319
7.	Bazilescu park	500	160	500	160	1484	317	1850	390	2103	408	---	---	294	334
8.	Romanian Shooting Fed.	670	210	1440	330	1440	350	1718	400	1900	400	---	---	327	347
9.	Geologic Museum	340	180	1250	310	1511	322	1935	376	1950	380	---	---	320	328
10.	NIEP site Magurele	370	250	1710	350	1710	350	1810	320	1739	337	2090	410	326	338
	All sites.	325	169	854	252	1243	320	1530	367	1832	386	2005	417		

$$\overline{V}_S = \frac{\sum_{i=1}^{n} h_i}{\sum_{i=1}^{n} \frac{h_i}{V_{Si}}} \quad (1)$$

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 (Romanian Code for the seismic design for buildings P100-1/2006 and EUROCODE 8). According to the same code, the weighted mean values $\overline{V}_S$, computed for at least 30 m depth, determine 4 classes of the soil conditions:

1. Class A , rock type : $\overline{V}_S \geq 760$ m/s;
2. Class B, hard soil : $360 < \overline{V}_S < 760$ m/s;
3. Class C, intermediate soil: $180 < \overline{V}_S < 360$ m/s;
4. Class D, soft soil: $\overline{V}_S \leq 180$ m/s;

All the $\mathbf{V_{S\text{-}30}}$ values in Table 1 belong to type C of soil after this classification (Romanian Code for the seismic design for buildings - P100-1/2006). Even the $\mathbf{V_{S\text{-}50}}$ values in the Table 1 fall in the type C of the classification.

All these data were stored in a database for the new borehole sites in Bucharest area (Table 1, after Bala *et al.*, 2007a). The database was built with the purpose of comparing the results with previous results from other seismic measurements in the area of Bucharest. The mean velocity values from Table 1 are close to other values previously measured by Hannich *et al.* (2006) and Bala *et al.* (2007b).
The second purpose for the database was to be ready as reliable input data for new modelling in other points in Bucharest where we have only the geologic profiles from the boreholes, but no geophysical measurements are available.

2. Spectral amplification curves computed for the 10 sites

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 by Kramer (1996). Here we apply an equivalent linear one-dimensional analysis, as implemented in the computer program SHAKE2000 (Ordónez, 2003). 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 variation in 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 (Ordonez, 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.

The recorded motion of the 27.10.2004 earthquake (Mw= 6) at K2 accelerometer station PRI in Bucharest was used as seismic input motion. All 3 components (one vertical and two horizontal components) were available. This accelerometer station is placed in the borehole near the City Hall site at 52 m depth. The strong motions PRI_EW (east-west component) and PRI_NS (north-south component) were used for modelling. The first strong motion PRI_EW was considered as being a representative acceleration recorded in a borehole of 52m depth, in Bucharest from a moderate Vrancea earthquake.
The results of the linear modeling with SHAKE2000 program for the 10 boreholes are presented in the **Figure 1** as spectral acceleration variation with the period. The greatest values are characterizing the sites Ecologic Univ.; Titan 2 Park; Bazilescu Park (EUNI, TITAP, BAZI).

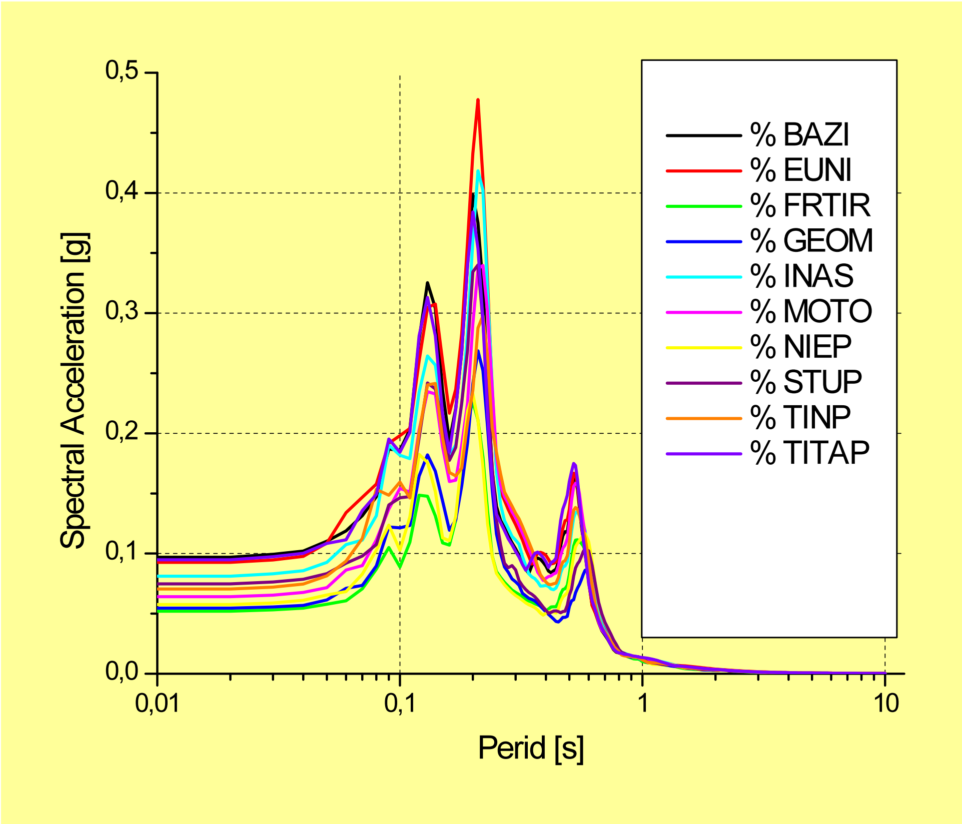

Figure 1. Spectral acceleration response computed with the input strong motion PRI_EW for the 10 boreholes in Bucharest.

In **Figure 1** the maximum values of the spectral accelerations occur around the 3 main values of the periods in Figure 10: T_1 = 0.13 s; T_2 = 0.2 s; T_3 = 0.55 s. The highest values resulted at the period T_2 = 0.2 s, and they are between 0.22 g and 0.48 g. The amplification factors computed for the 50 m thick sediments package, corresponding for this period are between 3.7 and 7.4 (for T_2 = 0.2 s). If we consider a comparison of the values at surface, they are between 0.22 g at Romanian Shooting Fed. (northern part of Bucharest) and 0.48 g (Ecologic Univ. in the central part of Bucharest).

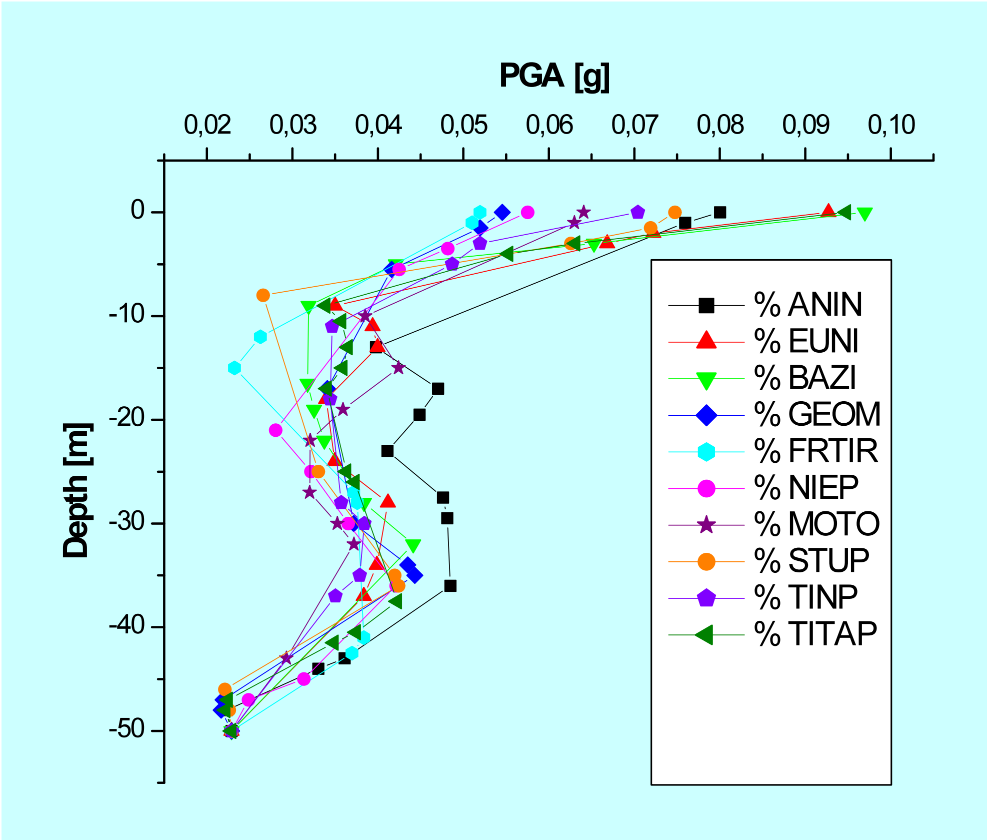

Figure 2. PGA variation with depth as result from linear modelling in the 10 boreholes in Bucharest.

The values of acceleration at surface are presented in the **Figure 2** 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 as 0.09 – 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 these layers.

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