Romanian Reports in Physics, Vol. 63, No. 1, P. 250–274, 2011

GEOLOGICAL AND GEOPHYSICAL MODEL OF THE QUATERNARY LAYERS BASED ON *IN SITU* MEASUREMENTS IN BUCHAREST, ROMANIA

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Received December 16, 2009

Abstract. The local surface geology, the soil behaviour as well as the local hydrogeological factors have a well-known influence upon the characteristics of the earthquake ground motion and the corresponding site effects. The geological and hydrogeological setting in Bucharest, the capital of Romania, as well as relative short recurrence intervals of strong intermediate-depth earthquakes in the Vrancea area, make necessary to study the geological cause of observed seismic site effects. In the case of Bucharest, the source geometry of the intermediate-depth Vrancea earthquakes remains almost the same in respect to the city area, the hypocentral distances being in the range of 160–220 km, while the epicentral distances for Bucharest are in the range of 100–130 km. Compared to these distances the spatial extend of Bucharest – of about 20 km is small. Influences due to source directivity and travel path effects can be assumed to be constant over the entire city area. In the latest moderate earthquakes recorded peak ground accelerations varied over the city area by a factor of up to 4. The high ground motions recorded across Bucharest during strong earthquakes in the past result from site-specific amplification within the city, obviously due to lateral variation of local soil and hydrogeologic near-surface conditions. To study this correlation it was necessary to know the geotechnical and dynamic properties of the involved geological layers.

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

1. INTRODUCTION

Starting with 2002, a lot of efforts within diverse research projects were undertaken to obtain reliable values for seismic shear-wave velocities of the different Quaternary layers. The first systematic research began between 1997–2007, but especially in 2003 and 2006, within the Collaborative Research Centre (CRC-461) performed by the University of Karlsruhe, Germany in collaboration with diverse research institutes from Bucharest, Romania. Two CERES projects between 2002–2005, initialised and supervised by the National Institute of Earth Physics (NIEP) from Bucharest brought further data at new sites. Additional data were obtained finally between 2006–2008, within a NATO-SfP project. The results obtained within all these research projects, as measured shear-wave velocities at different sites in Bucharest, are presented, compared and weighted for the individual Quaternary layers in this paper.

2. GEOLOGIC AND HYDROGEOLOGIC BACKGROUND OF THE BUCHAREST CITY AND SURROUNDINGS

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 700–1500 m depth (Mandrescu et al., 2004) and near the surface an alternation of up to 300 m thick Quaternary sand and clay layers and among them three main porous aquifer systems. Strong laterally heterogeneities and important vertical thickness variations of these soft soil deposits complicate the geologic structure.

2.1. Geomorphology

Bucharest is situated in the Romanian Plane, which extends between the Carpathian Mountains in the North and the Danube River in the South. The topographic altitudes in Bucharest vary between 65 and 95 m over the Black Sea level, reflecting a flat relief, slightly inclined toward southeast. The main geomorphologic characteristic of the city is minted by two likely parallel aligned rivers, oriented northwest-southeast, the Dambovita River in the southern part and the Colentina River in the northern part of the city. These two rivers are dividing the city area into three main geomorphologic units: the Dambovita-Colentina inter-fluvial domain between the two rivers, the Baneasa-Pantelimon Plain north of the Colentina River and the Cotroceni-Vacaresti Plain south of the Dambovita River. The higher situated plains represent practically terraces of the two rivers. The meadows of the rivers occupy about 10% of the city area, the meadow of the Dambovita river being larger, reaching to a maximum width of 1.0–1.5 km. The transition between the meadows and the terraces presents generally steep slopes.

2.2. Regional geology

The area of Bucharest is situated within the regional geological unit of the Moesian Platform, western part, which dates since the beginning of the Paleozoic era. The Moesian Platform comprehends two structural elements (since Mutihac, 1990; Raileanu et al., 1994):

– a crystalline basement of Precambrian chloritic and sericitic schists;

– a sedimentary cover, composed of marine, folded Paleozoic and Mesozoic formations. The greatest thickness of this sedimentary cover exceeds 14,000 m (Matenco 1997) in the foredeep of the Eastern Carpathians.

After a sedimentary subsidence of the Carpathian Foredeep during the Upper Tertiary and Quaternary, an asymmetric sedimentary basin results, Bucharest being situated at the southern margin of this southward thinning basin (Mutihac 1990). The thickness of the Tertiary sediments, reaching near the Carpathian Arc Bend to 8,000 m, appears reduced in the central area of Bucharest to about 500–1,000 m (since Ciugudean and Martinof, 2000). The Quaternary alluvial and lacustrine deposits presents in the area of Bucharest a thickness of about 200–300 m (since Liteanu 1952). Holocene loess-like sediments, recent alluvial material and anthropogenic backfill overly on the top the Quaternary deposits.

2.3. Classification of the Quaternary deposits

A first classification on the geological and lithological description of the Quaternary deposits in the Bucharest area was made by Liteanu 1952. This classification of 7 main layers (beginning from the surface to depth) is accepted until today (Lungu et al., 1999; Mandrescu et al., 2004; Bala et al., 2006) and was considerably improved through the researches of Ciugudean and Martinof 2000; Ciugudean-Toma and Stefanescu, 2006. 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 2–5 m in the “Dambovita-Colentina inter-fluvial domain”, 10–16 m in the northern and southern Plaines (Baneasa-Pantelimon and Cotroceni-Vacaresti) and 3–6 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*** containing up to 80% hard consolidated clay and calcareous concretions with intercalated thin sand and silt lenses. The thickness of this layer varies between 0–25 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 1–25 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.

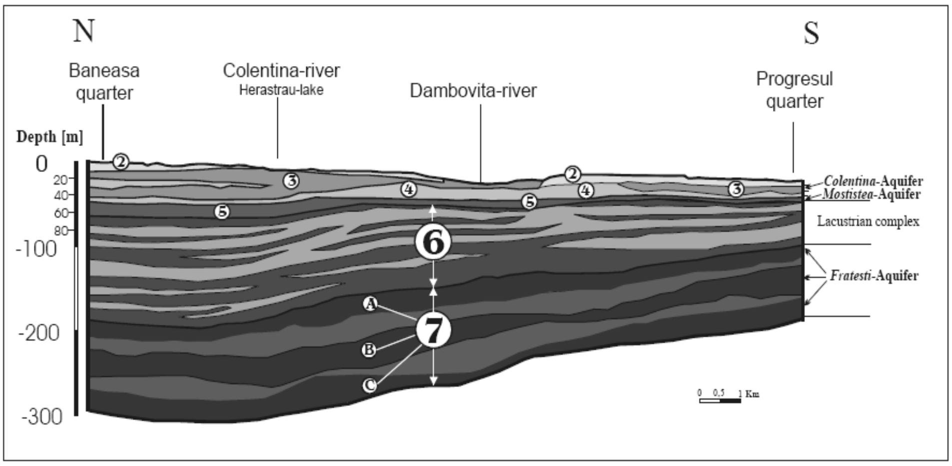

Fig. 1 – The 7 Quaternary layers and the 3 main aquifers in the geologic underground of Bucharest in a schematic a N-S section.

2.4. Hydrogeology

Complex hydrogeological conditions are characterizing the underground of Bucharest. Considering only the Quaternary deposits, these contain three main porous aquifer systems, each of them with lateral inhomogeneities and vertical thickness variations.

The upper-most aquifer, the “Colentina-aquifer” is connected to the Colentina gravel complex (layer 3). It is a phreatic aquifer in direct hydraulic connection with the alluvial deposits of the two rivers, Colentina and Dambovita.

A second aquifer, the “Mostistea-aquifer” is connected to the mentioned Mostistea-sandbank (layer 5), sands with mostly fine to medium grain size. This aquifer presents great variations of thickness in the area of Bucharest. It is a mainly confined aquifer, but being also at any places in hydraulic contact with the overlying Colentina-aquifer and also especially in the southern part of Bucharest with the surface water system, loosing there his confined character.

The deepest and thickest quaternary aquifer, the “Fratesti-aquifer” forms the base of the Quaternary layers (Fig. 1). It is a regional aquifer system with three distinguished aquifers named A, B and C, each of these 10–40 m thick, being extended continuously in the southern part of Romania, dipping toward the Carpathians and outcropping near the Danube. The most important aquifer of this system is the layer A, being mainly used for drinking water abstraction (Bretotean, 2001).

3. METHODS APPLIED IN BUCHAREST FOR THE DETERMINATION OF *IN SITU* SEISMIC VELOCITIES OF THE GEOLOGIC LAYERS

In the past, geotechnical information for the shallow geologic underground in Bucharest was obtained by some laboratory analyses and tests on samples of some of the drillings performed by the subway planning company METROUL S.A. in Bucharest. The horizontal and vertical distributions of the 7 Quaternary complexes (layers) are relatively well known through about 500 geotechnical exploration drillings, mainly provided by METROUL S.A. Bucharest (Ciugudean and Martinof, 2000; Ciugudean-Toma and Stefanescu, 2006). In order to use this existing geologic underground model for the evaluation of the dynamic soil behavior and further for seismic hazard, vulnerability and risk analyses, the corresponding share-wave velocities (V_s) as well as the density and thickness of each principal sedimentary layer must be known from in situ measurements in as many sites as possible.

Dynamic properties, especially shear-wave velocities were determined by Vertical Seismic Profiling (VSP) in some boreholes in Bucharest. First in one borehole at the National Institute for Building Research (INCERC) test site (Lungu et al., 1999) and afterward in few boreholes all over the city area of Bucharest. These available V_S -data were obtained mainly by the Institute of Geotechnical and Geophysical Studies (GEOTEC), the National Institute for Building Research (INCERC) and the Technical University of Civil Engineering Bucharest (UTCB) are cited in Hannich et al., 2005.

The National Center for Seismic Risk Reduction (NCSRR, Bucharest) performed in 2003 down-hole seismic measurements in seven boreholes in the northern part of Bucharest (Aldea et al., 2006) in cooperation with the Japan International Cooperation Agency (JICA). The deepest investigation depth reached 140 m at one of the sites. The seismic velocities resulted from these measurements are used only for $V_{S\text{-}30}$ analyses, because they were not correlated with the geology, namely the 7 Quaternary layers.

The first systematic seismic researches in Bucharest begin with the studies performed within the frame of the large interdisciplinary Collaborative Research Centre (CRC) 461: ***Strong Earthquakes: a Challenge for Geosciences and Civil Engineering.*** This Collaborative Research Centre was performed between 1997–2007 by the Karlsruhe University, Germany, together with several research institutes from Bucharest, Romania (http://www-sfb461.physik.uni-karlsruhe.de/pub). First, Multi-Offset Vertical Seismic Profiling measurements (MOVSP) were performed in May 2002 by a German company (Orlowski et al., 2003) in the frame of this large CRC 461. The results are thoroughly interpreted and correlated with existing geologic data for each site (Hannich et al., 2005).

Due to the poorly resolution of the MOVSP-method for the upper part of the boreholes (down to 35 m depth), another measuring method was chosen in a later stage, namely Seismic Cone Penetration Tests (SCPT). This method was applied at 10 different sites in Bucharest in 2006 within the same Collaborative Research Centre CRC-461. Through the measured cone resistance and sleeve friction, significant site-relevant in-situ state parameters were deduced as well as detailed shear-wave velocities were determined. For the sandy layers the variation of the share-wave velocity for fully saturated, partially saturated and practically dry conditions were analysed, showing the influence of the groundwater level upon the shear-wave velocity (Hannich et al., 2006).

Another geophysical campaign began with down-hole seismic measurements performed in 12 existing boreholes, during two Romanian research projects (CERES) performed in the period 2002–2005 under the supervision of the National Institute for Earth Physics (NIEP), Bucharest. Although the measurements were drastically limited by the field conditions and seismic noise in a very crowded city. Finally, good results were obtained down to 70–100 m and at some sites down to 150–200 m (Bala et al., 2006 and 2009).

The same method of down-hole seismic measurements was applied successfully in the frame of the NATO SfP project no. 981882, together with the Karlsruhe University, Germany: ***Site-effect analyses for the earthquake-endangered metropolis Bucharest, Romania.*** In the period 2006–2007 ten new boreholes were drilled down to 50 m in Bucharest, in order to obtain new geotechnical and seismic velocity data for the main part of the central area of the city. During drilling, core sampling for geotechnical studies from the main geologic layers were undertaken. The obtained shear-wave velocities represented reliable results for the upper 50 m depth in the Bucharest area, confirming however mostly the previous obtained values for the Quaternary layers by other applied methods (Bala et al. 2007; Ritter et al., 2007). Laboratory measurements on samples extracted from boreholes within the NATO-SfP project, offered new reliable values for the geotechnical characteristics of the main sedimentary units of the Bucharest area (Balan et al., 2007).

All the boreholes and measuring sites with their name, investigation depth, measuring method and research project are gathered in Table 1. Fig. 2 shows a map of Bucharest with the localization of these sites.

In the present paper the results obtained in the mentioned shear-wave velocity measuring campaigns in Bucharest are presented and discussed.

3.1. Multi-Offset Vertical Seismic Profiling (MOVSP) performed in Bucharest within the Collaborative Research Centre 461 of Karlsruhe University

The Multi-Offset Vertical Seismic Profiling method (MOVSP) is a version of the classic Vertical Seismic Profiling method (VSP). It is called also Walkaway-VSP method, because the seismic signals are produced at a lot of source-locations situated along profiles around the borehole. The seismic receivers (geophones) are installed inside the borehole at different depths. In Bucharest the seismic signals are produced at the surface by a mobile seismic vibrator. The boreholes used for measurements were all equipped with plastic casing to eliminate possible column waves of high velocity as those through steel casing, overlaying the expected useful signals. As well the boreholes must be filled for the measurements with water, because as seismic receivers were used hydrophones, installed along a cable-chain hanged in the center of the borehole. Figure 3 shows schematic the measuring principle of the applied MOVSP-measurement. The MOVSP-measurements in Bucharest were carried out by a german company in May 2002 (Orlowski et al., 2003). The results of the measurements are presented and discussed in Hannich et al., 2005. The main disadvantage of this method and the options applied in Bucharest were, that the upper part of the borehole could not be filled with water, due to the local hydraulic conditions of the geologic underground. Thus, for the upper 35 m of depth, respectively for the three upper Quaternary layers, no seismic velocities could be obtained.

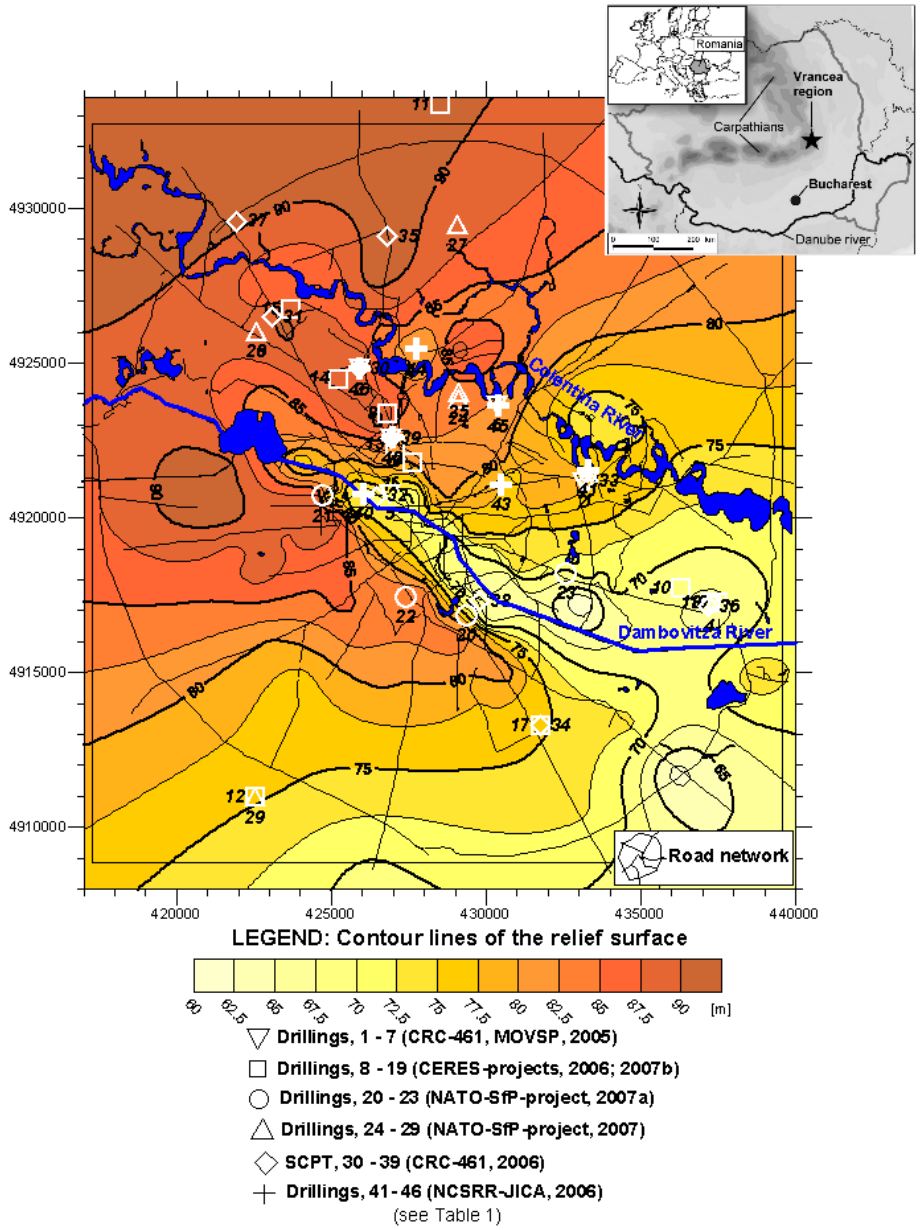

Fig. 2 – Map with area under investigation and measurement sites of the different drilling projects. The metropolitan region of Bucharest, Romania is mainly inside the characteristic ring road with a diameter of about 20 km. Contour lines of the relief surface are coloured in grey colours, lakes, rivers and channels are indicated in blue. The sites where drilling, core recovery and seismic measurements were done are indicated as different signs and numbers. The inset shows the geographical context with the Vrancea earthquake zone at the bend of the Eastern Carpathians. The coordinates are in the UTM system.

Table 1

Drillings and SCPT-locations used for seismic velocity measurements between 2002–2008 in Bucharest

No.	**Drilling /SCPT-location**	**Depth [m]**	**Method**	**References**
1	INCERC1	100	Multi-Offset Vertical Seismic Profiling (MOVSP)	CRC-461-project MOVSP Hannich et al., 2005
2	INCERC2	70		
3	EREN	60		
4	METROUL	80		
5	OPERA	58		
6	UTCB	70		
7	Piata Victoriei	150		
8	Grivita	110	Down-hole seismic measurements	CERES-project Bala et al., 2006 Bala et al., 2009
9	Politehnica	200		
10	Policolor	100		
11	Otopeni	200		
12	Magurele	112		
13	Iorga	170		
14	Foradex	81		
15	Buciumeni	150		
16	Bazilescu Park	172		
17	IMGB	155		
18	Centura 1	80		
19	Centura 2	60		
20	Tineretului Park	50	Down-hole seismic measurements	NATO-SfP-project Bala et al., 2007
21	Univ_Ecologica	50		
22	Inst_Astronomic	51		
23	Titan2 Park	50		
24	Motodrom Park	51	Down-hole seismic measurements	NATO-SfP-project Ritter et al., 2007
25	Student Park	50		
26	Bazilescu Park	50		
27	Romanian Shooting Fed.	50		
28	Geologic Museum	50		
29	NIEP – Magurele	50		
30	AGRO	30	Seismic Cone Penetration Test (SCPT)	CRC-461-project, SCPT Hannich et al., 2006
31	BAZI	27		
32	EROI	31		
33	INCERC	30		
34	IMGB	22		
35	INMH	32		
36	METRO	37		
37	MOGO	32		
38	TINE	27		
39	VICT	33		
40	Municipal Hosp.	69	Down-hole seismic measurements	NCSRR-JICA-2003 Aldea et al., 2006
41	NCSRR/INCERC	140		
42	Piata Victoriei	110		
43	UTCB-Pache	66		
44	Civil Protection	68		
45	UTCB-Tei	78		
46	City Hall	52		

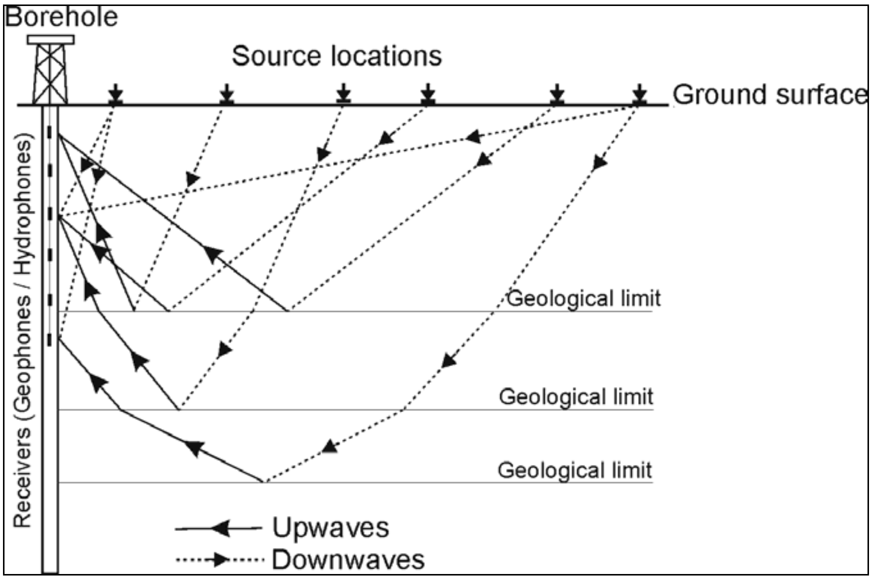

Fig. 3 – Schematic measuring arrangement (sources and receivers) and possible wave travel paths during Multi-Offset Vertical Seismic Profiling.

For the geologic Quaternary layers mean weighted velocity values for compressional wave (Vp) and sharewave (Vs) are computed in each borehole according to the following formula:

$$\bar{v}_s = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{v_{si}}}, \tag{1}$$

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

The obtained mean weighted seismic velocities at 6 sites from Bucharest are presented in Table 2. For the Quaternary layer 3 only one result emerged from the borehole EREN: 340 m/s. Only 3 results are certified for the upper part of the deep Quaternary layer 7 with an average of 511 m/s. In two of the boreholes an important result is obtained for deep Quaternary layers, down to 200–300 m depth, for which share-wave velocities of 525–530 m/s are certified.

Table 2

Mean weighted seismic velocities for the geologic layers 3 – 7 determined in 6 sites in Bucharest based on the MOVSP-measurements

	Geologic Layer No.	**3**		**4**		**5**		**6**		**7**	
		Mean weighted seismic velocity values [m/s]									
No. in Table 1 & Fig. 2	**Borehole site**	V_p	V_s	V_p	V_s	V_p	V_s	V_p	V_s	V_p	V_s
1.	INCERC1 (100 m)	–	–	1468	373	1692	425	1767	450	–	–
2.	INCERC2 (70 m)	–	–	1550	400	1447	386	1765	457	1870	530
3.	EREN (60 m)	1300	340	1836	432	1696	392	1714	400	–	–
4.	METROUL (80 m)	–	–	1170	–	1671	502	1683	413	1968	512
5.	OPERA (58 m)	–	–	1767	372	1728	371	–	–	–	–
6.	UTCB (70 m)	–	–	1490	–	1741	405	–	–	–	–
7.	Piata Victoriei (150 m)	–	–	1453	400	1682	367	1782	415	1826	477
	Seismic velocity values [m/s]	**1,300**	**340**	**1,607**	**391**	**1,673**	**392**	**1,751**	**429**	**1,930**	**511**

3.2. Down-hole seismic measurements within Romanian CERES projects between 2002–2005

In situ seismic velocity measurements were carried out in the period 2002 – 2005 in Bucharest in 12 boreholes as classical down-hole seismic measurements in the frame of two Romanian research projects (CERES) under the supervision of the National Institute for Earth Physics (NIEP).

Number [8–19], name and position of the boreholes are presented in Table 1 and Fig. 2. In two of the boreholes (number 18 and 19) the measurements were done in the frame of the CERES Project 34 (2002–2003) and presented in Bala et al., 2005. The measurements made in the other of 10 were performed in the frame of the CERES Project 3-1 (2003–2005) and presented in Bala et al., 2006 and Bala et al., 2009.

The geophones used are 3-component geophones, clamped mechanical on the borehole wall. The chosen recording offset was 1 m. The shot point was situated at a distance of 10–30 m from the borehole and the wave generation was performed by hammer blows on a wooden block. After the data processing, by filtering and several corrections applied, as well as the correlation with the depth intervals of the corresponding Quaternary layers in each borehole, compressional and shear-wave velocities are obtained.

Table 3

Mean weighted seismic velocities for the 7 main Quaternary layers determined at 12 sites from Bucharest by classical down-hole measurements within two CERES-projects

	Geologic layer no.	**1**		**2**		**3**		**4**		**5**		**6**		**7**	
No. in Table 1 & Fig. 2		**Mean weighted seismic velocity values [m/s]**													
	Borehole site	V_p	V_s	V_p	V_s	V_p	V_s	V_p	V_s	V_p	V_s	V_p	V_s	V_p	V_s
8.	Grivita (110 m)	–	–	–	–	–	–	875	400	1100	354	1535	398	–	–
9.	Politehnica (200 m)	–	–	833	227	1076	227	1211	335	1797	353	1731	444	1746	508
10.	Policolor (100 m)	298	153	975	288	1140	284	1544	305	1544	305	1828	383	–	–
11.	Otopeni (200 m)	500	187	1034	187	1034	250	1034	354	1333	354	1740	403	1666	523
12.	Magurele (112 m)	–	–	–	–	1492	260	1000	309	1413	325	1725	415	1818	512
13.	Casa Iorga (170 m)	–	–	–	–	594	240	2600	292	2600	280	1953	384	1815	528
14.	Foradex (81 m)	–	–	600	270	1500	270	2200	305	1519	356	1906	349	–	–
15.	Buciumeni (150 m)	–	–	400	181	541	243	1555	278	1977	321	1727	369	–	–
16.	Bazilescu Park (172 m)	–	–	430	150	642	179	2151	291	1820	384	1786	517	–	–
17.	IMGB (155 m)	–	–	960	370	1203	393	1541	362	1541	362	1716	400	1725	628
18.	Centura 1 (80 m)	298	153	460	249	1465	337	2129	326	1677	289	1670	439	–	–
19.	Centura 2 (60 m)	300	150	600	230	1450	230	1880	333	1754	391	–	–	–	–
	Mean weighted seismic velocity	**370**	**167**	**631**	**223**	**989**	**254**	**1,580**	**319**	**1,518**	**350**	**1,755**	**405**	**1,740**	**544**

The locations of the 10 boreholes, as well as of the last two boreholes (Centura 1 and Centura 2) previously measured and published are presented in the Figure 2 (drillings 8–19). The boreholes were protected with plastic tubes or steel tubes and seismic measurements are performed down to the bottom of each borehole. These are presented in Table 3 together with mean weighted values for each layer and each borehole, as well as averaged values for each layer and for all 12 sites.

It can be noted, that for the upper two layers, 1 and 2, the seismic velocities could be deduced only in a few boreholes, generally due to the small thickness of the layers. The seismic velocities in the deepest Quaternary layer, number 7, could be measured only in five of the 12 boreholes. As a particularity may be noted, that at the site no. 16, “Bazilescu Park”, for the layers 2 and 3 are obtained relative low values for the shear-wave velocity. At the time of their measuring, this seems strange and difficult to explain, but later, other more detailed measurements by SCPT method, confirmed these low values (Hannich at al., 2006).

3.3. Down-hole seismic measurements within a NATO SFP-Project between 2006–2008

In the frame of the NATO SfP-Project 981882 drilling and seismic measurements were performed in the period 2006–2008. Ten boreholes were drilled down to 50 m depth and equipped with plastic tubes to reduce the column-waves. Core sampling was done while drilling to obtain geotechnical data of the geologic layers. Seismic velocity measurements of Vp and Vs by the classic down-hole method are executed. The results are presented in Table 4.

Because the depth of the boreholes was limited to 50 m, the deepest Quaternary layer no. 7 was not intercepted. Shear-wave velocities were recorded as well in the upper two layers, in all of the ten boreholes.

Table 4

Mean weighted seismic velocities for the Quaternary layers within the NATO SfP-project in 10 boreholes of 50 m depth in Bucharest.

	Geologic Layer no.	**1**		**2**		**3**		**4**		**5**		**6**	
No. in Table 1 Fig. 2	**Borehole site**	**Mean weighted seismic velocities [m/s]**											
		V_p	V_s	V_p	V_s	V_p	V_s	V_p	V_s	V_p	V_s	V_p	V_s
20.	**Tineretului Park**	180	140	570	220	856	299	–	–	1666	398	–	–
21.	**Ecology Univ.**	300	120	1180	220	1250	241	1610	354	1850	390	2042	401

22.	**Astronomy Institute**	200	120	914	260	1200	330	1440	350	1900	390	2124	433
23.	**Titan2 Park**	290	160	800	250	800	250	980	350	1576	381	1850	450
24.	**Motodrom Park**	650	200	650	200	1320	320	1827	393	1980	410	2050	410
25.	**Student Park**	490	210	490	210	1361	342	1570	370	1607	375	1820	400
26.	**Bazilescu park**	500	160	500	160	1484	317	1850	390	2103	408	–	–
27.	**Romanian Shooting Fed.**	670	210	1440	330	1440	350	1718	400	1900	400	–	–
28.	**Geologic Museum**	340	180	1250	310	1511	322	1935	376	1950	380	–	–
29.	**NIEP Magurele**	370	250	1710	350	1710	350	1810	320	1739	337	2090	410
	Mean weighted seismic velocity	**325**	**169**	**854**	**252**	**1,243**	**320**	**1,530**	**367**	**1,832**	**386**	**2,005**	**417**

3.4. Seismic Cone Penetration Tests (SCPT) performed in Bucharest in 2006 within the Collaborative Research Centre 461 of Karlsruhe University

To improve the results of the measured shear-wave velocities for the upper 30–35 m, Seismic Cone Penetration Tests (SCPT) were performed within the Collaborative Research Center (CRC)-461 at 10 sites in Bucharest in 2006. These measurements have enabled to obtain new dynamic characteristics for the penetrated geologic layers in the upper 35 m and particularly for two shallow aquifers existing in this depth-interval. Shear-wave velocities of the corresponding sandy layers under fully saturated, partially saturated and practically dry conditions could be obtained, showing quite different values.

Cone Penetration Testing (CPT) is the most versatile device for soil investigation. Without disturbing the ground, it provides information about the soil type, geotechnical parameters like shear strength, density, elastic modulus, rates of consolidation, etc. The Seismic Cone Penetration Test (SCPT) is also a reliable technique to determine in-situ seismic wave velocities.

The Seismic Cone Penetration Test (SCPT) uses in addition to the conventional CPT-system a seismic acquisition system consisting by three main components: a seismic wave source (hammer-and-beam source for S-waves), a seismic (piezo) cone penetrometer and a recording unit as a PC-based acquisition software. Principally travel times of body waves propagating between the wave source on the ground surface and an array of geophones in the cone penetrometer are measured. In this way combined high resolution standard CPT results and seismic wave velocities are presented in parallel, permitting a good correlation of seismic profiling data with stratigraphical, lithological and geotechnical parameters.

The results of the SCPT-measurements were used first of all for a detailed geological and geotechnical description of the penetrated soil layers. In a second step, the seismic measurements were used to obtain a detailed attribution of the share-wave velocities to specific lithological layers with specific geotechnical characteristics. In addition, for the sandy and gravelly layers, variations of the share-wave velocity can be correlated with fully saturated, partially saturated and dry parts of these layers. Finally, based on the standard CPT' s pertinent evaluations of the liquefaction potential, the probability of liquefaction and of the safety index of liquefaction by empirical relations were deduced (Hannich et al., 2006).

The mean weighted share-wave velocity for the first 30 m depth (V_{S-30}) is presented in Table 5, for each of the 10 sites.

Table 5

V_{S-30} determined from SCPT-measurements at 10 sites in Bucharest

No. in Table 1 & Fig. 2	**Name of the SCPT location**	**V_{S-30} share-wave velocity [m/s]**
30.	AGRO	311
31.	BAZI	267
32.	EROI	287
33.	INCERC	305
34.	IMGB	251
35.	INMH	264
36.	METRO	303
37.	MOGO	281
38.	TINE	237
39.	VICT	290

4. VALUATION AND COMPARISON OF THE MEASURED SHEAR-WAVE VELOCITIES BY DIFFERENT METHODS

For the study of site effects in Bucharest within the Collaborative Research Centre 461, the necessity appeared to know over the whole city area the shear-wave velocities of the Quaternary layers. In the past only in a few boreholes seismic velocities were measured, but with unsatisfactory results. To close this gap, characteristic shear-wave velocities were first determined using Multi-Offset Vertical Seismic Profiling (MOVSP) technique applied in 7 boreholes (6 sites) in Bucharest (Orlowski et al., 2003). After these first seismic velocity measurements (Hannich et al., 2005), other measurements by similar methods and different techniques at divers sites are performed in Bucharest during several Romanian and international research projects.

Because the shallow Quaternary layers in Bucharest present relatively great laterally changes in thickness partly in lithology (Hannich et al., 2005; Bala et al., 2006; Ciugudean-Toma and Stefanescu 2006), the only way to get reliable geotechnical and seismic velocity data may be guarantied by in-situ measurements in boreholes or by special methods on the surface, as those presented in the present paper. To overcome the heterogeneities of thickness and lithology, integrative velocity values applicable over the whole city area of Bucharest were deduced. The shear-wave velocities obtained by different methods and within several research projects were used to determine mean weighted values for each of the seven Quaternary layers in the area of Bucharest. These mean weighted seismic velocities are presented in Table 6, for each of the seven Quaternary layers in Bucharest. The depth of the main Quaternary layers presented in Table 6 are averaged values observed from many borehole measurements in Bucharest (Ciugudean-Toma and Stefanescu 2006).The average densities presented in Table 6 are actual densities recorded after laboratory measurements in the NATO SfP Project 981882, the single experiment which comprised core sampling of the sedimentary layers and used to determine geotechnical values for each layer under laboratory conditions (Balan et al., 2007).

The mean shear-wave velocities obtained by the MOVSP method (CRC-461 Program) in 7 boreholes in Bucharest are presented in column 4 (Hannich et al., 2005). They show especially for the geologic layers 3, 4 and 5 precise values, relative close to other values obtained later. For the first 2 layers no values could be determined, due to technical problems of the method.

In column 5 are presented averaged values of the share-wave velocities obtained by down-hole measurements in 12 boreholes in Bucharest within the Romanian CERES projects (Bala et al., 2006 and Bala et al., 2009). The values obtained for the first 3 layers (1 –3), but only in some of the boreholes, are among the first results measured in-situ for these near-surface layers in Bucharest.

An important contribution with average shear-wave velocities for the shallow layers 2–5, down to 28–33 m depth (column 6), brought the SCPT measurements (CRC-461 Program) performed in Bucharest at 10 sites (Hannich et al., 2006). The values are based on detailed shear-wave velocity measurements and are mainly close to those of column 5.

Column 7 presents the mean shear-wave velocities obtained within the NATO-SfP Project 981882 at 10 sites in Bucharest. The boreholes especially drilled for this purpose down to 50 m depth provided reliable seismic velocity values for the upper 6 layers, 1–6 (Bala et al., 2007 and Ritter et al., 2007)

Special seismic velocity measurements performed on refraction profiles at 2 sites in Bucharest, at the Tineretului Park and at the Bazilescu Park (von Steht et al., 2008). In columns 8 and 9 are presented the obtained shear-wave velocities for comparison.

Table 6

Comparison of mean shear-wave velocity values obtained by different research projects and methods for the Quaternary layers in Bucharest between 2002–2008

Number and name of the Quaternary layer	**Depth of upper limit**	**Density**	**MOVSP method** (7 boreholes) V_s CRC 461-Program (2003)	**Down-hole method** (11 boreholes) V_s CERES-Projects (2002–2005)	**SCPT method** (10 sites) V_s CRC-461-Program (2006)	**Down-hole method** (10 boreholes) V_s NATO-SfP-Project 981882 (2006–2008)	**Refraction profiles** (2 sites) V_s CRC 461-Program (2006)	
1	2	3	4	5	6	7	8	9
	[m]	[g/cm³]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]
1. Backfill	0	1.75	–	167	–	169	140–175	175–195
2. Upper Clay layer	0.5–5	1.96	–	223	248	252	275–280	230
3. Colentina layer	5–12	2.05	340	254	263	320	315–350	300–345
4. Intermediate Clay layer	10–20	2.02	391	319	296	367	–	360
5. Mostistea sandbank	15–35	2.05	392	350	331	386	–	–
6. Lacustrine layer	35–50	2.14	429	405	–	417	–	–
7. Fratesti layer (A)	00–180	2.05	511	544	–	–	–	–

The average values of shear-wave velocities presented above in Table 6 are generally very close, although they were measured by quite different methods in boreholes, by penetration tests or at the surface in Bucharest. The narrow range in which the mean shear-wave velocities for each of the geologic layer are placed, allow us to use them for the evaluation of mean values for each of the seven Quaternary layers.

4.1. Model of the seven Quaternary layers in Bucharest characterized by mean shear-wave velocities and mean densities

Averaging the values from Table 6, mean shear-wave velocities for each of the seven Quaternary layers were obtained and are presented in Table 7, together with the respective standard error values. Mean densities for the seven layers, presented in both Tables 6 and 7, were deduced by averaging densities obtained by laboratory measurements on core samples from drillings within the mentioned NATO SfP project.

In Fig. 4 are presented synthetically variations with depth of the mean shear-wave velocities and the mean densities of the layers. It may be observed that the mean shear-wave velocities present a continuous increase with depth, while the mean densities present also small reversals for layer 3 and 7. It must be mentioned that for particular boreholes/sites also the measured shear-wave velocities present local reversals for some sub-ranges of the different layers. These reversals of the share-wave velocity appear mainly in the layers 3 and 4, where also the standard errors reach peak values.

Local areas with smaller shear-wave velocities mainly within layer 3 (Colentina sandy/gravelly layer) were observed in the Dambovita-River meadow and in the northwestern part of Bucharest – around the Bazilescu-Park area. These areas will be outlined as lower $V_{s\text{-}30}$ areas in the corresponding contour map.

Table 7

Mean shear-wave velocities and mean densities of the seven Quaternary layers in Bucharest

Number of the Quaternary layer	**Mean depth to the middle of the layer**	**Mean Density /layer**	**Mean V_s /layer**	**Standard error**
	[m]	[g/cm³]	[m/s]	[m/s]
1	2,5	1,75	169,6	5,7
2	7,5	1,96	246,1	10,6
3	12,5	2,05	305,3	18,5
4	23	2,02	346,6	19,2
5	40	2,05	364,7	14,6
6	85	2,14	417	6
7-A	160	2,05	527,5	11,7

A special attention must be focused on the deepest Quaternary layer, layer 7 (Fratesti), considered in a recent paper (Mandrescu et al., 2007) as so-called engineering bedrock. As known, to consider a layer as engineering bedrock, this must present a significant velocity contrast in comparison with the velocities of the overlying layers. This could not be observed by the in-situ measurements mentioned in the present paper. Mandrescu et al., 2007 supposed shear-wave velocities of about 600–700 m/s (not direct measured values) in his paper, much higher than our effective measured values (mean 528 m/s). Further the measured velocities present a continuous increasing sequence from the surface to depth, without any step at the interface between layer 6 and 7.

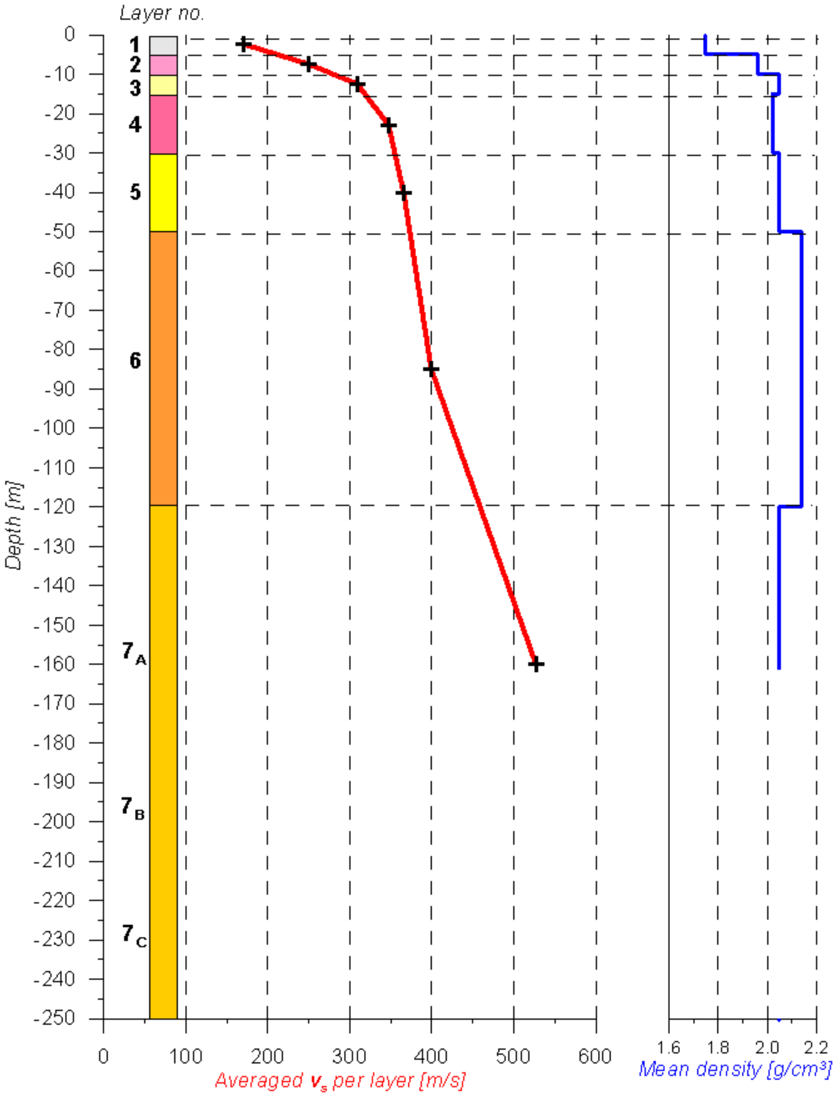

Fig. 4 – Variation with depth of the mean shear-wave velocities and the mean densities of the Quaternary layers in Bucharest.

The mean values of velocities and densities presented in this paper (Table 7 and Fig. 4) represent a new geophysical model, which will be used together with the already elaborated geologic 3D-model for Bucharest (Kienzle 2003) for the computation of response spectra and transfer functions by linear modeling. Based on these further microzonation studies for Bucharest will be outlined.

5. V_{S-30} AND V_{S-50} SEISMIC VELOCITIES FOR BUCHAREST

Using the shear-wave velocities obtained by different measuring methods in boreholes and by the SCPT-method and presented in chapter 3, mean weighted seismic velocity values for the first 30 m depth (V_{S-30}), respectively 50 m depth (V_{S-50}) were deduced for 36 sites, using the formula (1) from Chapter 3.1. These velocity values are presented below in Table 8.

In Table 8 were included at the positions 40–46 also down-hole seismic measurements performed by the National Center for Seismic Risk Reduction (NCSRR) of Bucharest. NCSRR instrumented in cooperation with the Japan International Cooperation Agency (JICA), beginning with 2003, seven boreholes in the northern half of Bucharest (Aldea et al., 2006). The results of these measurements were used also in this paper to deduce mean weighted seismic velocities until 30 m and 50 m depth.

The mean weighted values V_{S-30} and V_{S-50} presented in Table 8 may be used in concordance with EUROCODE 8 and the Romanian Code P100-1/2006 for the seismic design of buildings, for future planning of buildings in Bucharest. According to the specified codes, the weighted mean values of the V_{S-30} shear-wave velocity, correspond to 4 classes of soil conditions:

1. Class A, rock type : $\bar{V}_S \geq 760$ m/s;
2. Class B, hard soil : $360 < \bar{V}_S < 760$ 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.

According to these codes, the elastic response spectra characterizing the 4 classes of the soil conditions will be determined using the methodologies in the international practice.

It can be observed that all the V_{S-30} values from Table 8 are situated within a range from 219–331 m/s, indicating soil-type C. Even the V_{S-50} values in the Table 8 indicate soil-type C.

Table 8

Mean weighted shear-wave velocities for the first 30 m depth ($V_{S\text{-}30}$) and 50 m ($V_{S\text{-}50}$) at different sites in Bucharest

No. in Fig. 1	Borehole	$V_{S\text{-}30}$	$V_{S\text{-}50}$	References
9	Politehnica_200	297	310	Bala et al., 2006; Bala et al., 2009.
10	Policolor_100	286	292	
11	Otopeni_200	243	274	
12	Magurele_112	290	313	
13	Iorga_170	245	255	
14	Foradex_81	296	315	
15	Buciumeni_150	256	281	
16	Bazilescu_172	247	248	
18	Centura 1	288	318	
19	Centura2	261	292	
20	Tineretului Park	262	304	Bala et al., 2007
21	Univ_Ecologica	286	324	
22	Inst_Astronomic	283	320	
23	Titan2 Park	299	339	
24	Motodrom Park	288	327	Ritter et al., 2007
25	Student Park	295	320	
26	Bazilescu Park	294	331	
27	Romanian Shooting Fed.	327	347	
28	Geologic Museum	307	328	
29	NIEP-Magurele	326	337	
30	AGRO	311	–	Hannich et al., 2006
31	BAZI	267	–	
32	EROI	287	–	
33	INCERC	305	–	
34	IMGB	251	–	
35	INMH	264	–	
36	METRO	303	–	
37	MOGO	281	–	
39	VICT	290	–	
40	Municipal Hospital	245	281	Aldea et al., 2006
41	NCSRR/ INCERC	270	302	
42	Victoriei Plaza	284	310	
43	UTCB -Pache	288	318	
44	Civil Protection	293	309	
45	UTCB – Tei	309	326	
46	City Hall	219	258	

A new map of $V_{S\text{-}30}$ for Bucharest is presented in Fig. 5 by contouring the velocity values in Table 8. White areas in the map represent areas without velocity data.

Analyzing the $V_{s\text{-}30}$-map for Bucharest in Fig. 5 it may be observed that two areas with lower $V_{s\text{-}30}$ values were outlined: an area along the Dambovita-River meadow between the Municipal Hospital and the Tineretului-Park and another area in the north-western part of Bucharest between the Bazilescu-Park and Baneasa site. Within these two areas $\mathrm{V}_{s\text{-}30}$ -values down to 243–250 m/s were observed.

The interfluvial area, between the Colentina-River and the Dambovita-River is characterized by higher values, in the range of 290–300 m/s and locally greater, until 330 m/s. The southern plain is characterized by medium velocity values, around 290 m/s as well as the eastern part of the northern plain also by values around 290 m/s.

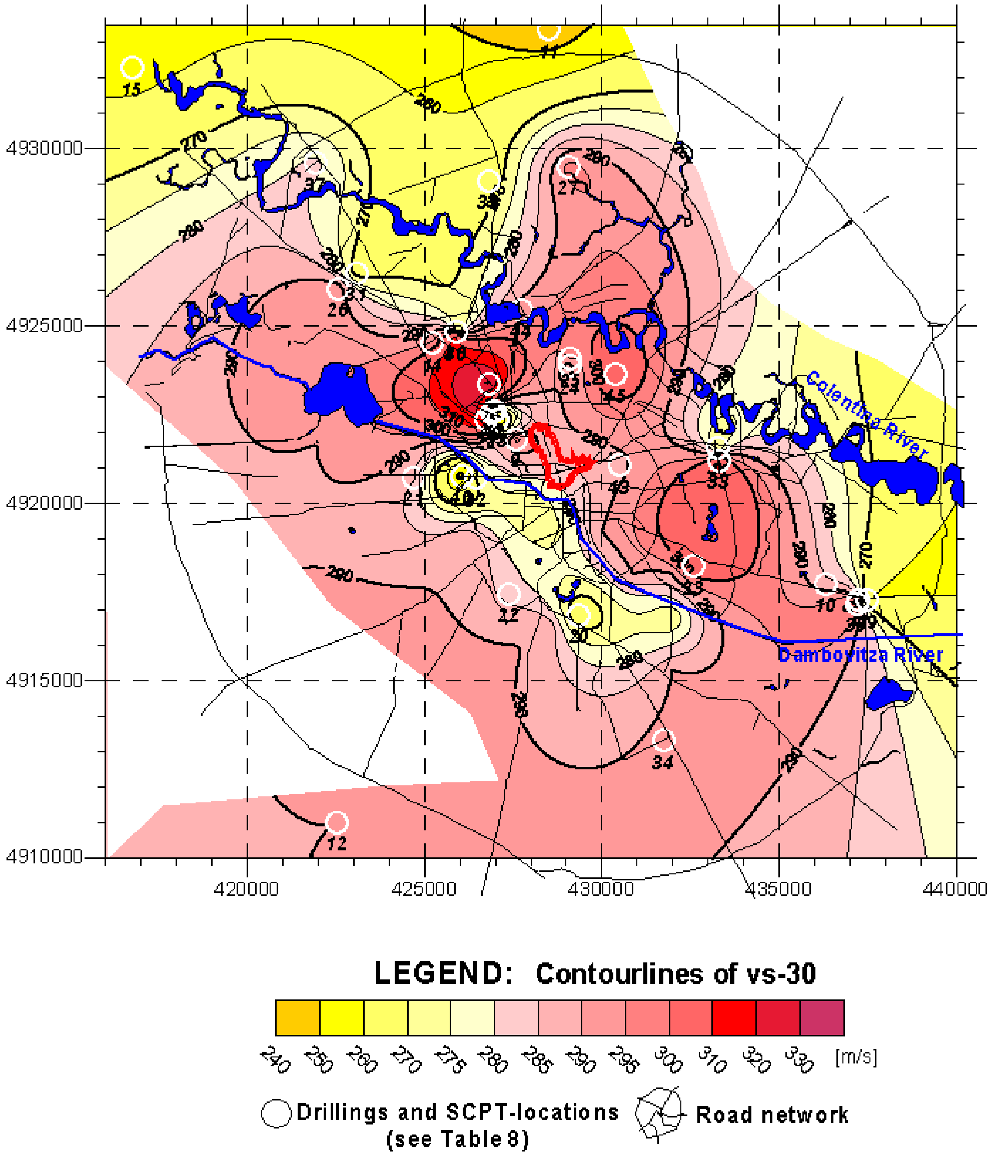

Fig. 5 – Contour-map of the mean weighted shear-wave velocity ($V_{s\text{-}30}$) for Bucharest. Isolines are in [m/s]. Coordinates are given in UTM system.

6. CONCLUSIONS AND OUTLOOK

Starting with 2002, a lot of efforts within diverse research projects were undertaken to obtain reliable values for seismic shear-wave velocities of the different Quaternary layers. The first systematic research began between 1997–2007, but especially in 2003 and 2006, within the Collaborative Research Centre (CRC-461) performed by the University of Karlsruhe, Germany, in collaboration with diverse research institutes from Bucharest, Romania. The National Institute of Earth Physics from Bucharest initialised and supervised also within several national and NATO-SfP research projects similar measurements to complete the database.

Because the shallow Quaternary layers in Bucharest present relative great laterally changes in thickness partly in lithology (Hannich et al., 2005; Bala et al., 2006; Ciugudean-Toma and Stefanescu, 2006), the only way to get reliable geotechnical and seismic velocity data may be guarantied by in-situ measurements in boreholes or by special methods on the surface, as those presented in the present paper.

To overcome heterogeneities of thickness and lithology, integrative velocity values applicable over the whole city area of Bucharest were deduced. The shear-wave velocities obtained by different methods and within several research projects were used to determine mean weighted values for each of the seven Quaternary layers in the area of Bucharest.

The mean weighted shear-wave velocities presented in this study for Bucharest (Table 6) are enclosed generally in a narrow domain, attesting the good quality of the applied in-situ measurements of different types (Tables 2–5). Especially the shear-wave velocities obtained for the first three Quaternary layers are very important and are among the first results obtained by in-situ measurements for these layers in Bucharest.

The mean values of shear-wave velocities and densities of the Quaternary layers presented in this paper represent a new geophysical model for Bucharest (Table 7 and Fig. 6). It will be used together with the already elaborated geologic 3D-model for Bucharest (Kienzle et al., 2006) to compute enhanced response spectra and transfer functions by linear modelling methods. These will be used in further microzonation studies and assessment of seismic hazard for Bucharest. They are gathered in a database, which is a valuable collection of elastic and dynamic parameters obtained by direct in-situ measurements.

To fulfil the requirements of the EUROCODE 8 and the Romanian Code P100-1/2006 for the seismic design of buildings, shear-wave velocity values for the first 30 m depth ($V_{S\text{-}30}$), respectively 50 m depth ($V_{S\text{-}50}$) at different sites were also deduced in this paper. A new map of $V_{S\text{-}30}$ for Bucharest is presented by contouring the deduced velocity values in 36 sites. Two areas with lower $V_{s\text{-}30}$-values were outlined with values down to 243–250 m/s, in comparison with values of 290–330 m/s in the remaining part.

The elastic and dynamic parameters for the 7 Quaternary layers presented in this paper are valuable tools for further microzonation studies and the assessment of seismic hazard for Bucharest, the capital of Romania. They are gathered in a database, which is a valuable collection of elastic and dynamic parameters obtained by direct in-situ measurements. Further studies of site effects and amplification ratio will be initiated based on this updated database, using linear or non-linear modelling approaches, in order to outline important details in the microzonation of Bucharest, Romania.

Acknowledgments. This work was supported by CNCSIS – UEFISCDI, project number PNII – IDEI ID_78/2008: *Seismic local effect studies by interdisciplinary modeling employing equivalent-linear and non linear methods*.

Part of the data presented was acquired during the ANCS project number PNII – CAPACITATI 31038/2007 conducted by National Institute of Research and Development for Earth Physics.

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