SHEAR-WAVE VELOCITY DATABASE – A KEY INPUT FOR SEISMIC SITE AMPLIFICATION MODELS IN BUCHAREST, CAPITAL OF ROMANIA

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The evaluation of seismic hazard at local scale, with the contribution of strong-motion data from a dense seismic network and insightful geological and geophysical data, is one of the key components in seismic risk mitigation. Significant efforts were made to record and predict the highly variable peak spectral amplification values of strong seismic motion in Bucharest, capital city of Romania, especially after the 4 March 1977 Vrancea earthquake with a moment-magnitude of 7.4, which resulted in 1424 victims in the city (90% out of the national total). Research was made to evaluate seismic site effects, as a result of the continuously growing dataset of seismic, soil-mechanic and elasto-dynamic parameters recorded in the field, but to this date there is no official microzonation map issued. In this paper we review studies referring to shear wave velocity (V_S) measurements in the area of Bucharest – as key input for seismic site amplification models and microzonation maps, selecting and reprocessing some data in order to obtain a homogenized database. This contains mean weighted V_S values for the uppermost 30 m, 50 m, 70 m and 100 m depth intervals. By mapping and interpreting the distribution of values we provide additional means for future microzonation studies, highlighting also the importance of using deeper than 30 m V_S measurements.

Key words: shear-wave velocity; site amplification; microzonation; seismic hazard; Bucharest.

1. INTRODUCTION

In local seismic hazard (microzonation) studies, the availability of accurate local determination of the shallow soil layers characteristics is very important in order to determine the local response under various seismic scenarios. The result of 1D, 2D and 3D modelling can reflect the local variability of the soil package, leading to the understanding of potential building damage and measures of seismic risk mitigation (Thitimakorn 2013). In large cities located on thick layers of sediments (such as Bucharest – capital of Romania), affected also by earthquakes with variable source parameters, detailed input data regarding geological and geophysical data but also real strong motion recordings (at surface and in boreholes) are important for determining relevant building design parameters. The largest amplification of the soil will occur at the lowest natural frequency or its fundamental frequency (Bălă *et al.*, 2009a), which corresponds to the characteristic site period. In situ measurements of shear wave velocity (V_S) and soil thickness provide a direct measure of the characteristic site period. Seismic noise measurements are an accessible method and computed H/V spectral ratio can also provide a good indication on the fundamental frequency of the site. New seismic methods for measuring and determining V_S have been derived and tried in Bucharest in recent years.

Mean weighted shear-wave velocity in uppermost 30 m depth interval ( ) is considered by Eurocode 8 (European Committee for Standardization, 2004) and the Romanian Seismic Design Code P100–1/2013 (UTCB, 2013) to be usually a useful indicator in seismic hazard assessment – revealing areas with generic variations of average seismic velocities. However, for seismic site amplification models and nonlinear site response analyses in areas with thick layers of sediments such as most major cities, might not reflect adequately the soil characteristics leading to significant amplification variabilities (Cioflan *et al.*, 2009; Yordkayhun *et al.*, 2015; Yaghmaei-Sabegh & Rupakhety 2020).

The city area of Bucharest presents geological conditions which, in the context of strong motion induced by intermediate-depth earthquakes in the Vrancea Seismic Source (occurring typically at 60–150 km located 130–190 km hypocentral distance away from the city), leads to significant local site amplification (Mărmureanu *et al*., 2016) and variability of parameters at surface and as such different damage distribution (Toma-Danila & Armaș 2017). Among the key geological features are:

- the absence of hard bedrock down to Cretaceous upper limit at 500–1500 m depth (Lăcătușu *et al*., 2007);
- an alternation up to 300 m of thick Quaternary sand and clay layers near surface;
- 3 main porous aquifer systems among the sand and clay layers;
- strong lateral heterogeneities and important vertical thickness variations of soft soil deposits and aquifers complicating the geologic structure.

Recent several studies (among which Cioflan *et al*., 2009, Bălă *et al*., 2014 and von Steht *et al*., 2008) have emphasized that V_S is important but must be known until deeper depths (of 100–150 m for example) for Bucharest. These values are one of the key input data to algorithms which estimate the spectral acceleration response and transfer functions for every site in which in situ measurements are performed (such as *SHAKE*). As such, in this study we review many recent studies presenting measured V_S values (by different methods) in the Bucharest area and select representative values in order to obtain a homogenized database of mean weighted V_S values at 30, 50, 70 and 100 m. Some values are reprocessed and elevation is extracted from the Digital Elevation Model (DEM) EU-DEM versions 1.1. Maps revealing a broader than previous studies (such as Arion *et al*., 2012, Bălă *et al*., 2010 or Kienzle *et al*., 2006) extent of V_S values are then generated and interpreted.

2. QUATERNARY DEPOSITS IN BUCHAREST CITY AREA

2.1. GENERAL CLASSIFICATION

A first classification on the geological and lithological description of the Quaternary deposits in the Bucharest area is found in Liteanu (1952) and comprise seven main sedimentary complexes (beginning from the surface). The model was considerably improved by Ciugudean-Toma & Ștefănescu (2006), by analysing the probes from several hundreds of boreholes performed in the years 1980’ for the subway of Bucharest. The classification is accepted until today by almost all the scientists involved in the studies of seismic site amplification models and geological modelling, such as Lungu *et al*., (1999), Aldea *et al*., (2006), Mărmureanu *et al*., (2010), Bălă *et al*., (2011), Bălă *et al*., (2013), or Manea *et al*., (2016).

This classification comprises the following names and general characteristics (after Bălă & Hannich 2021):

- **Layer 1: *Anthropogenic backfill and soil***, with a thickness varying between 3–10 m
- **Layer 2: *Upper clayey-sandy complex*** representing Holocene deposits of loess, sandy clays and sands; the thickness of this complex varies between 2 and 5 m in the inter-fluvial domain, 10-16 m in the northern and southern plain and 3–6 m in the river meadows
- **Layer 3: *Colentina gravel complex***, bearing the *Colentina aquifer*, is a layer containing gravels and sands with varying grain size distribution
- **Layer 4: *Intermediate clay layer*** contains up to 80% hard consolidated clay and calcareous concretions with intercalated thin sand and silt lenses; the thickness of this layer varies between 0 and 25 m.
- **Layer 5: *Mostiștea sandbank*,** bearing the *Mostiștea aquifer*, is a sand layer with sands of medium to fine grain size. The thickness varies in the area of Bucharest between 1 and 25 m.
- **Layer 6: *Lacustrine complex*** (or *Lagoon complex*) is composed by a variation of limy-marled clay and fine sands, the grain size < 0,005 mm consisting about 86%.

The thickness varies from about 60 m in the southern part of Bucharest to about 130 m in the North. The variable thickness is due to the underlying *Frățești complex* which descends northward.

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

A more detailed description of the geotechnical characteristics of each layer is given by Ciugudean-Toma & Ștefănescu (2006), which analyse probes from boreholes, presenting the main characteristics of the layers in the depth, in points distributed over the city (figure 1). Mostly due to the characteristics of quaternary deposits in Bucharest, under the influence of seismic waves originating from intermediate-depth Vrancea earthquakes, nonlinear effects have been observed (Cioflan *et al.*, 2009; Mărmureanu *et al.*, 2016) during the 4 March 1977 (moment-magnitude Mw 7.4; 94 km depth), 30 August 1986 (Mw 7.1; 131 km depth) and 30 May 1990 (Mw 6.9; 91 km depth) events (Fig. 1).

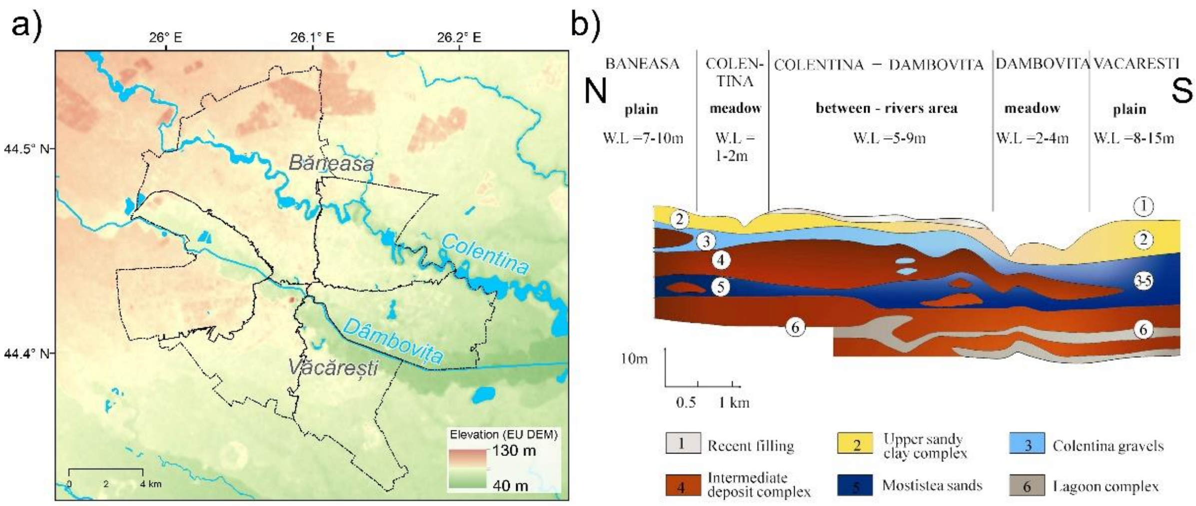

Figure 1 – a) Topographic map of Bucharest (data source: EU-DEM version 1.1.) and b) schematic geomorphologic section (N-S direction), with principal shallow sedimentary layers; depth scale is exaggerated. The section is modified after Ciugudean-Toma & Ștefănescu (2006

2.2. V_S CHARACTERISTICS

For the study of site effects in Bucharest, the necessity to acquire more reliable values of V_S of for Quaternary layers emerged in the years 1997–1999. After these first seismic velocity measurements at INCERC site, other seismic measurements by similar methods and different techniques were performed in Bucharest sites during several Romanian and international research projects.

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

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

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. According to the same design code, for $\overline{V}_{S30}$, 4 classes of the soil conditions are defined:

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

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

Another critical value in site effects is to estimate characteristic period of the site, defined as period of vibration corresponding to the package of layers from a certain depth to the surface. The vibration period of soil layers in the upper 30 m (T_{S30}) is calculated using Equation 2 in UTCB (2013):

$$T_{S30} = \frac{4h}{\overline{V}_S} \tag{2}$$

where: *h* is ground depth of 30 m.

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

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

Table 1

Comparison of $\overline{V}_S$ values [m/s] obtained by different methods for the Quaternary layers in Bucharest between 2002–2009 (modified after Bălă *et al*., 2011)

Number and name of the Quaternary layer	Density [g/cm³]	MOVSP method (7 boreholes) 6 sites	Down-hole method (12 boreholes)	SCPT method (10 sites)	Down-hole method (10 boreholes)	Boreholes measured by UTCB/ NCSRR Down-hole method (7 sites)	Refraction profiles		Mean value and standard deviation
							site A	site B	
1. Backfill	1.75	–	167	–	169	195	140–175	175–195	175.2 m/s ± 8.19 %
2. Upper clay layer	1.96	262	223	262	252	265	275–280	230	253.4 ± 7.99
3. Colentina layer	2.05	340	254	267	320	327	315–350	300–345	308.3 ± 8.19
4. Intermediate Clay layer	2.02	391	319	296	367	364	–	365	350.3 ± 8.19
5. Mostiştea sandbank	2.05	392	350	322	386	405	–	–	371 ± 9.2
6. Lacustrine layer	2.14	429	405	–	417	–	–	–	417 ± 2.8
7. Frăţeşti layer (A)	2.05	511	544	–	–	–	–	–	527.5 ± 4.4

The $\overline{V}_S$ values obtained using different methods such as in boreholes, by penetration tests SCPT or at the surface in Bucharest (seismic refraction) are generally very close. The average densities presented in table 1 are actual densities determined after laboratory measurements in the NATO SfP Project 981882 – the experiment including core sampling of the representative sedimentary layers and determining the geotechnical values for each layer under laboratory conditions (Bălă *et al*., 2011).

Because the shallow Quaternary layers in Bucharest present relative great laterally changes in thickness and also in lithology, the only way to get reliable geotechnical and seismic velocity data may be guaranteed by in situ measurements in boreholes or by special methods on the surface. In order to use the values presented in table 1 for modelling of acceleration response spectra in random points of the Bucharest map, one needs to know the 3D exact position of the seven complexes in the underground of the Bucharest area – a difficult task which shall be completed in the near future with the aid of methods such as Manea *et al*., (2016). For now, the goal in present study is making a database with $\overline{V}_S$ values at standardized depth intervals, as we further present.

3. V_S DATABASE FOR THE BUCHAREST CITY AREA

3.1. DATABASE CHARACTERISTICS

To overcome the problem of heterogeneities of thickness and lithology, providing homogenized input for seismic site amplification models, integrative $\overline{V}_S$ values applicable throughout the whole city area of Bucharest were deduced for four fixed depth intervals (30 m; 50 m; 70 m; 100 m), with no link to the 7 layers earlier presented. V_S values obtained by different methods and authors are used in this database and weighted using equation (1). Final results are organized in a spreadsheet table (available at Toma-Danila *et al*., 2021), which mentions the original data references (shown also in table 2) and also provides interactive mapping, through Microsoft Excel's 3D maps module. Some of the site coordinates had to be redetermined, given the limitations in GNSS determination at the period of the measurement or the decimal degree accuracy and errors in report papers (there are references of modifications in the database) (Table 2).

In table 2 and in the database (Toma-Danila *et al*., 2021) there are:

- 55 points (drillings and SCPT locations) with $\overline{V}_{S30}$ values;
- 48 points for $\overline{V}_{S50}$ values;
- 21 points with $\overline{V}_{S70}$ values;
- 15 sites with $\overline{V}_{S100}$ values.

Values of $\overline{V}_S$ for the 30 m, 50 m depth intervals are between 180 m/s and 360 m/s, so they belong to Class C according to the Romanian Seismic Design Code (UTCB, 2013). For the 70 m and 100 m depth intervals there are a few $\overline{V}_S$ values higher than 360 m/s but without surpassing 390 m/s. In the following subchapters we present the main characteristics of reference data (Figure 2).

Table 2

Drillings and locations used for seismic velocity measurements performed in Bucharest and reported by different authors; all locations are shown on a map in figure 2

No.	Drilling /SCPT-location	Symbol of site	Depth [m]	Method	References
1	INCERC1	INC1	70	CRC 461 Project MOVSP 2002–2003 Multi-Offset Vertical Seismic Profiling (MOVSP)	Orlowsky *et al*., 2003; Hannich & Orlowsky, 2014
2	INCERC2	INC2	100		
3	EREN – AGR	AGR	60		
4	METROUL	MET	100		
5	OPERA – Calea Plevnei	OPE	58		
6	UTCB Tei	UTC	70		
7	Victoriei Square	VIC	150		
8	Grivita	GRIV	110	CERES Project 34, 2002–2003 CERES Project 3–1, 2003–2005	Bălă *et al*., 2005; Bălă *et al*., 2006; Bălă *et al*.,2007; Bălă *et al*., 2009
9	Politehnica	POLT	200		
10	Policolor	POLI	100		
11	Otopeni	OTOP	200		
12	Magurele	MAG	112		

No.	Drilling /SCPT-location	Symbol of site	Depth [m]	Method	References
13	Iorga	IOR	170	Down-hole seismic measurements	
14	Foradex	FORA	81		
15	Buciumeni	BUCU	150		
16	Bazilescu Park	BAZP	172		
17	IMGB	IMGB1	155		
18	Centura 1	CEN1	80		
19	Centura 2	CEN2	60		
20	Tineretului Park	TINE	50	NATO SfP Project 981882 2006–2009 Down-hole seismic measurements	Bălă *et al*., 2007
21	Ecological University	EUNI	50		
22	Astronomic Institute	INAS	51		
23	Titan2 Park	TITAP	50		
24	Motodrom Park	MOTO	51		Ritter *et al*., 2007; Bălă *et al*., 2007; Bălă *et al*., 2008a; Bălă *et al*., 2010
25	Student Park	STUP	50		
26	Bazilescu Park	BAZI1	50		
27	Romanian Shooting Fed.	FRTIR	50		
28	Geology Museum	GEOM	50		
29	National Institute of Earth Physics – Magurele	NIEP	50		
30	Agronomy	AGRO	30	CRC 461 Project Seismic Cone Penetration Test (SCPT) 2003–2005	Hannich *et al*., 2006
31	Bazilescu Park	BAZI2	27		
32	Eroilor	EROI	31		
33	INCERC Institute	INCERC	30		
34	IMGB	IMGB2	22		
35	Meteorological Institute	INMH	32		
36	METRO	METRO	37		
37	Mogosoaia	MOGO	32		
38	Tineretului Park	TINE	27		
39	Victory Square	VICT	33		
40	Basarab Bridge	BAS	30	Down-hole measurements	Lungu & Călărașu 2005
41	A1 Tineretului Park	TINA1	70–90	Seismic refraction lines	vonSteht *et al*., 2008
42	A2 Tineretului Park	TINA2	70–90		
43	A3 Tineretului Park	TINA3	70–90		
44	B4 Bazilescu Park	BAZP4	60–80		
45	B5 Bazilescu Park	BAZP5	60–80		
46	UTCB – Tei	UTC1	78	NCSRR-JICA 2003–2005 Down-hole seismic measurements	Aldea *et al*., 2006; UTCB Report Project 31–038/2007–2008
47	UTCB – Pache Protopopescu	UTC2	66		
48	NCSRR/INCERC	INC	140		
49	Civil Protection	PRC	68		
50	Victoriei Square	VIC	110		
51	City Hall PRI	PRI	52		
52	Municipal Hospital	SMU	69		
53	UTCB – Plevnei	UTC3	30		
54	Sos. Straulesti	SSA	50	Down-hole seismic measurements performed by the research group from UTCB	
55	Romexpo1	EXP1	51		
56	Sos. Fabrica de Glucoza	FGA	50		
57	Obor	OBO	50		
58	Baneasa Forrest	BAN	51		
59	Timpuri Noi	TNO	52		
60	Sos. Floreasca	FLO	50		
61	Romexpo2	EXP2	50		
62	National Park	PNA	50		

No.	Drilling /SCPT-location	Symbol of site	Depth [m]	Method	References
63	Titan 2 Park	PTI2	51		
64	Calea Victoriei	VIC2	52		
65	Sos. Nordului	NOR	50		

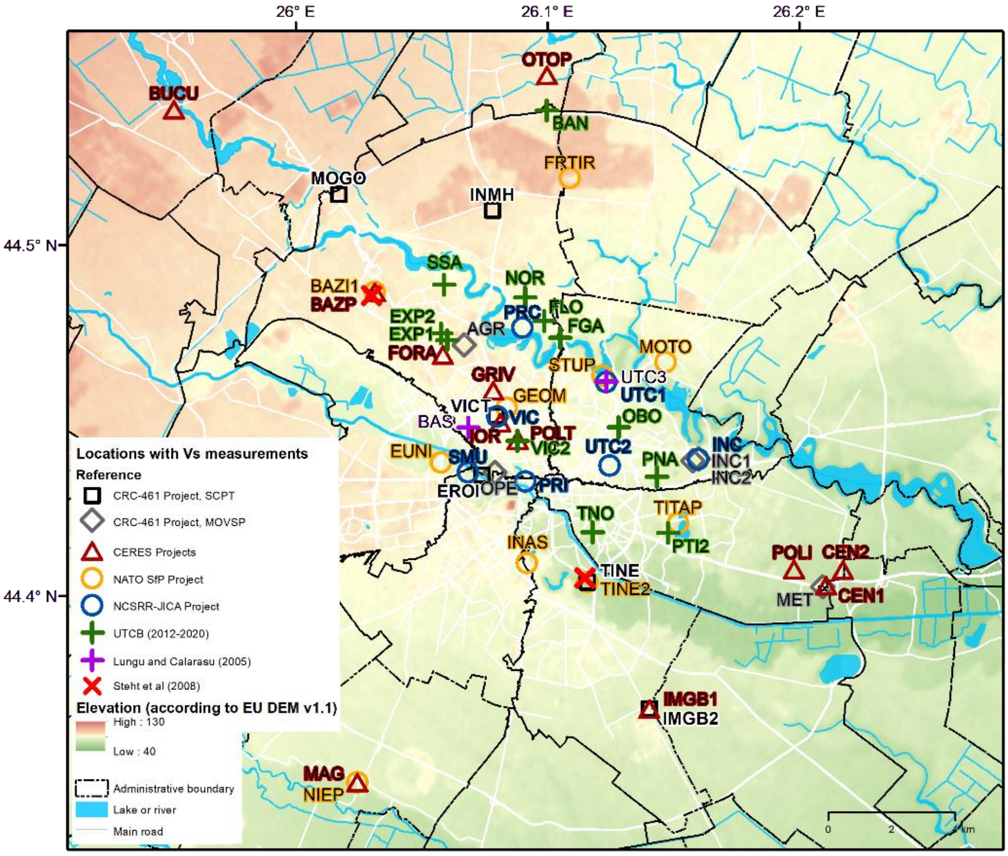

Figure 2 – Map with area under investigation and measurement sites of the different projects and measurement campaigns. The metropolitan region of Bucharest, is mainly inside the characteristic ring road with a diameter of about 20–21 km. The sites with drilling, where seismic and SCPT measurements were done, as indicated by different signs. The red crosses represent the 2 sites where seismic refraction lines were performed.

3.2. CLASSIC DOWN-HOLE MEASUREMENTS REPORTED AT THE END OF 1990'S

In situ measuring and gathering of geotechnical and geophysical data is reported in the late 1990's. Some drillings are reported near the Building Research Institute (INCERC) and some lithological columns appear related to two boreholes: FM3-113 near INCERC (drilling was made before 1989 down to 73 m) and F536 at EREN (74 m). Both are reported in Lungu *et al*., (1997).

In order to find the dynamic properties of the INCERC soil profile, which was considered as a test site, two boreholes were drilled and measured by Institute for Geotechnical and Geophysical Studies (GEOTEC S.A.): INCERC 1 and INCERC 2, in the frame of joint research program CRC 461. For INCERC 2 are presented both the lithological column and the corresponding Vs values down to 77 m depth (Lungu *et al*., 1997). A later borehole (INCERC 3) was drilled in 1998, down to 203 m depth, in order to be instrumented with a borehole accelerometer. In this borehole, a thorough downhole geotechnical measurement was performed by ATLAS-GIP S.A. down to 200 m depth (for layers 4–7), especially for averaged densities of the main geologic layers (Hannich *et al*., 2014).

It is worth to note that 15 specimens extracted from borehole INCERC 2 were from the soil layers 4 and 6, and they were measured in laboratory in order to determine the shear strain modulus ratio G/G_0 versus shear strain as well as the variation of the damping ratio D with shear strain. They were appropriate for low and respectively medium shear strains (Lungu *et al*., 1999).

3.3. MULTI-OFFSET VERTICAL SEISMIC PROFILING (MOVSP) PERFORMED WITH THE COLLABORATIVE RESEARCH CENTRE (CRC) 461 OF KARLSRUHE UNIVERSITY

The MOVSP method 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 were 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 were filled for the measurements with water, because hydrophones are used as seismic receivers, which are installed along a cable-chain hanged in the centre of the borehole (Bălă *et al*., 2011). The MOVSP measurements in Bucharest were carried out in May 2002 and the method and results were published by Orlowski *et al*., (2003). The results of the measurements for each borehole are presented and discussed in Hannich *et al*., (2014). The main disadvantage of this method is 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 uppermost 30–35 m depth intervals, respectively for the first three upper Quaternary layers, the seismic velocities could not be obtained. For four sites we have used the values determined later by SCPT method in the same sites, so that we have a complete profile with V_S values (INC1, INC2, EREN, METRO, AGR).

3.4. DOWN-HOLE SEISMIC MEASUREMENTS WITHIN A NATO SFP PROJECT

In the frame of the NATO SfP Project 981882, 10 drillings (20–29 sites in table 2), accompanied by seismic measurements, were performed in 2006–2008 (Bălă *et al*., 2010). The operation was completed by almost continuously core sampling while drilling, leading to the determination of geotechnical properties from each geologic layer after laboratory measurements. Following the completion of the drillings, seismic velocity measurements of V_P and V_S by the classic down-hole method were executed.

Because the depth of the boreholes was limited to 50 m, the deepest Quaternary layer (Frătești layer) was not intercepted. V_S values were recorded from surface down to layers 5 or 6, in all of the ten boreholes, at every meter.

The average densities presented in table 2 are actual densities recorded according to Ciugudean *et al*., (2006), after measurements of several hundred of cores from boreholes of Metroul S.A. laboratory measurements in the frame of NATO SfP Project 981882 – the single experiment used yet to determine geotechnical values (including density) for each layer under laboratory conditions (Bălă *et al*., 2007).

3.5. SEISMIC CONE PENETRATION TESTS (SCPT) PERFORMED IN 2005–2006

To improve the results of the measured V_S for the upper 30–35 m, SCPT were performed within CRC 461, at 10 sites in Bucharest, in 2005–2006 (30–39 sites in table 2). These measurements enabled to obtain new dynamic characteristics for the penetrated geologic layers in the upper 30–32 m and particularly for two shallow aquifers existing in this depth interval. V_S of the corresponding sandy layers under fully saturated, partially saturated and practically dry conditions were obtained – showing quite different values (Hannich *et al*., 2006).

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. 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 (Hannich *et al*., 2006).

The results of the SCPT measurements were used first of all for a detailed geological and geotechnical description of the penetrated soil layers. 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 in Bucharest by empirical relations was deduced (Bălă & Hannich 2021).

3.6. SITES MEASURED DURING THE NCSRR-JICA COOPERATION IN 2003–2006 AND LATER BY UTCB

Digital seismic equipment donated by the Japan International Cooperation Agency (JICA) to the National Center for Seismic Risk Reduction (NCSRR, Romania) allowed the development of a mixt seismic network in Bucharest, beginning with 2003. In 2005–2006, the network administered by NCSRR contained three types of instrumentation: (i) free-field stations – outside the capital city Bucharest (8 accelerometers); (ii) instrumented buildings - in Bucharest (5 buildings); (iii) stations with free-field and borehole sensors – in Bucharest: 7 sites with ground surface sensor and sensors in boreholes – sites 46–53 in table 2 (after Aldea *et al*., 2006; Aldea *et al*., 2007). The boreholes in which the seismic sensors were placed were previously measured by classic down-hole measurement and the results are presented in table 2. From 2003, the down-hole PS logging measurements have been carried out in Bucharest sites in cooperation by UTCB and NCSRR.

Down-hole PS logging have been used as simple and non-invasive geophysical technique for measuring seismic waves velocities, with a depth investigation ranging from 30 m up to more than 140 m. The impulse source of energy is generated at the ground surface, shear wave records being obtained by striking a wood plank horizontally and in opposite direction, while compression wave by dropping a wood hammer on the ground. The velocity sensor is composed by three geophones (2 horizontal and 1 vertical). During down-hole measurements, the sensor was lowered in borehole up to a predetermined depth investigation, being blocked on boring wall for detecting the waves generated by the surface source at 1m depth interval. The equipment system used for velocity measurements was composed of GEODAS acquisition station and PS Logging sensor.

V_S are usually measured by down hole measurements, but later, new methods such as MASW method were employed to obtain V_S values in the first 20 m from surface, at UTCB – Tei site (Arion *et al*., 2012). Seismic measurements performed by the research group from UTCB were performed in the years 2011–2018 employing down-hole measurements in boreholes down to 50–52 m depth for different local applications. These measurements are included in the database (54–65 sites in table 2).

3.7. V_S DERIVED WITH SASW AND MASW

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

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

For 7 sites where ground survey was conducted by both down-hole (Arion *et al*., 2012) and MASW methods, a comparative analysis of V_S values corresponding to each depth interval in soil profile has been performed by Călărașu *et al*., (2018). V_{S30} data obtained from MASW are ranging from 189 m/s to 302 m/s, while the values obtained by down-hole are in the range 263–309 m/s. The differences percentages of 15–35% are probably due to constrains of depth investigation limitation, sensors sensitivity, procedure and equipment specificity and lateral discontinuities of soil profile. From both examples presented here we have chosen the values obtained by down-hole to be included in our database.

3.8. OTHER METHODS OF DERIVING V_{S30} AT GLOBAL OR REGIONAL SCALE

Wald & Allen (2007) proposed a methodology that correlates topographic slope data from 30 arc-sec topographic data (recorded by the Shuttle Radar Topography Mission – SRTM30) and V_{S30} values obtained from different sites in USA and several other countries. The results were extrapolated and used to create a global map for V_{S30} values, being available on the USGS server (at https://earthquake.usgs.gov/data/vs30/). However, after farther testing in Europe and Middle East (Wald & Allen, 2007), the recommendation was for the method to be applied with caution for local or site-specific first order studies.

Neagu *et al*., (2018) made a selection of 19 sites in Bucharest in which previously measurements for seismic velocities were performed by PS logging. They found that the difference between seismic borehole measured values and topographical slope estimated values of $\overline{V}_{S30}$ may vary between –23% and +28% for Bucharest. These errors are considerably larger than the computed errors determined in table 2, of about 8–10%. Considering the range of topographical slope estimated values determined for Bucharest, we consider that the results of V_S are not reliable enough for entering in the database for the determination of local seismic hazard in Bucharest, because they will introduce a great amount of uncertainty in the research results.

3.9. PREVIOUS DETERMINATION OF MEAN WEIGHTED V_S

$\overline{V}_S$ values appear in the studies about Bucharest microzonation after 2000. Some $\overline{V}_{S30}$ and $\overline{V}_{S60}$ values are cited in Lungu & Călărașu (2005) – from which we use the record from Basarab bridge (table 2). Bălă *et al*., (2006) have added 3 new values for Politehnica, Policolor and Otopeni.

Aldea *et al*., (2007) provided mean weighted velocities ($\overline{V}_{S30}$ and $\overline{V}_{S52}$), as well as for the whole depth of each borehole which belong to the group of 7 sites which was geophysically examined prior to installation of accelerometers in boreholes.

$\overline{V}_S$ occurred in other studies about Bucharest sites for example in Bălă *et al*., (2008) and Bălă *et al*., (2009a; 2009b). In the second study, a list of 38 sites and 28 sites was used to construct maps for $\overline{V}_{S30}$ and $\overline{V}_{S50}$.

4. MAPS OF THE AVERAGE WEIGHTED V_S

Before mapping the database $\overline{V}_S$ values, data adjustments had to be performed. Different measurement campaigns took place in sites which have been previously used in other campaigns; due to poor descriptions and not precise determination of measurement points, this complicates the identification of some sites and potential duplication. From table 2 we have used some SCPT measurements (no. 30, 31, 33, 36) to complete the previous MOVSP measurements in places where they overlap. In other sites there were also several measurements performed in the same boreholes; for the INCERC test site (Figure 2) we have considered only the last performed measurements presented by Aldea *et al*., (2006) – INC site and the 2 measurements presented by Hannich *et al*.,

(2014) – INCERC1 and INCERC2 sites. Also, 2 sites with MOVSP measurements (UTCB and Victoriei Square) were excluded from the computation, because the values from later measurements in the same sites were preferable.

Sites 41–45 in table 2 represent short refraction lines (up to 300 m), located in 2 parks in Bucharest: Tineretului park (3 lines) and Bazilescu park (2 lines). They are documented in vonSteht *et al*., (2008). However, the velocity values for these sites were not considered for our $\overline{V}_S$ maps, given the method limitations and multiple values per profiles, but only for validation and discussions.

Database values were used to generate (through interpolation), maps of $\overline{V}_S$ at 4 depth intervals, from the surface: 30 m, 50 m, 70 m and 100 m (Figure 3 and Figure 4).

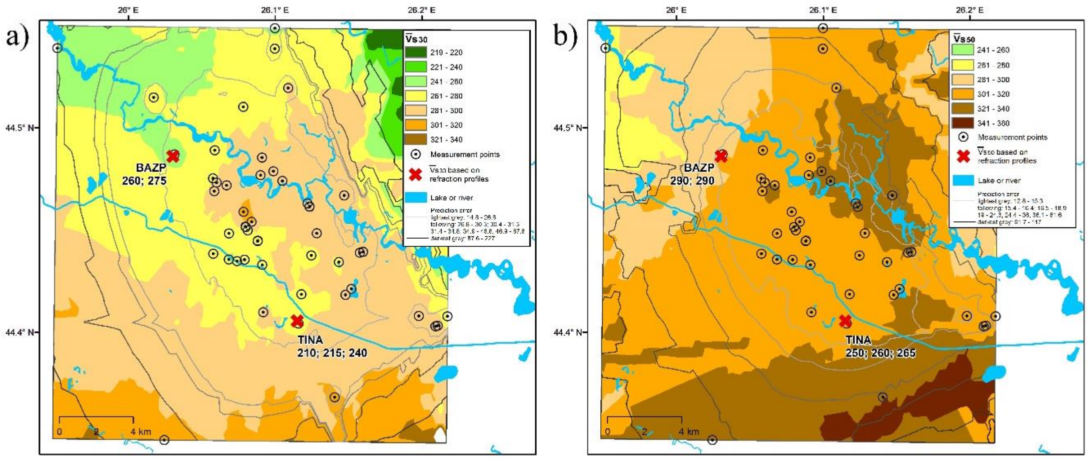

Figure 3 – Maps showing the result of Kriging interpolation of the $\overline{V}_S$ values at some of the sites considered in figure 2 for Bucharest, considering 2 depth intervals: a) 30 m; b) 50 m.

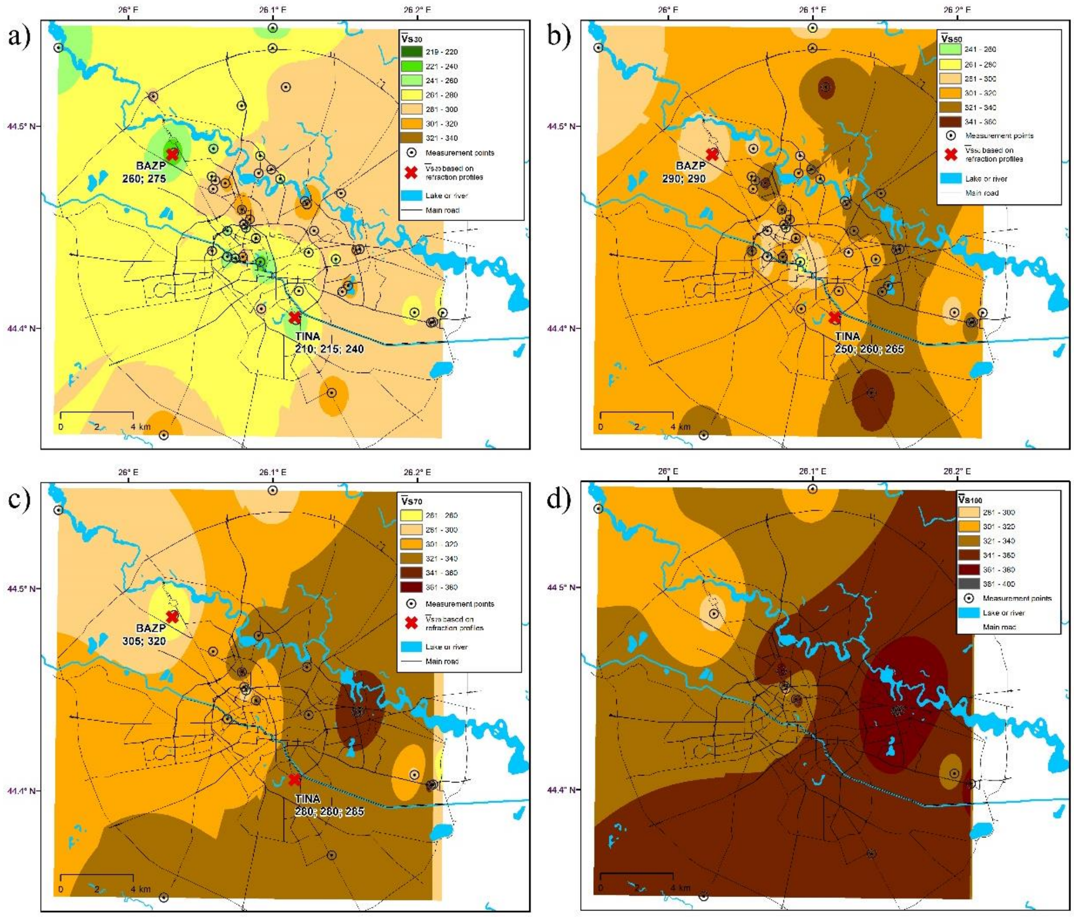

Figure 4 – Maps showing the result of IDW interpolation of the $\overline{V}_S$ values at some of the sites considered in figure 2 for Bucharest, considering 4 depth intervals: a) 30 m; b) 50 m; c) 70 m; d) 100 m.

In order to show an estimate of the expected $\overline{V}_S$ distribution throughout the city, two different sets of maps were created, based on our database, by using two different interpolation methods often used in geophysics (Sun and Kim 2017; Ghazi *et al*., 2014):

1. The kriging method of universal type (figure 3). For this, the parameters chose after multiple testing (due to a better fit of the model to the semivariogram) were Local Polynomial Interpolation of power 1 for trend removal, an account of anisotropy and eight search sectors.

2. The Inverse-Distance Weight (IDW) interpolation method (Figure 4). For this, we used a 12-point influence.

The degree of complexity of each method is different, but in conjunction they can show if a trend maintains or not. IDW assumes that each input point has a local influence that diminishes with distance and is able to keep values of observation in the specific points (but not exceed the minimum and maximum input values); however, it cannot reflect the errors in prediction. This is on the other side the benefit of the more advanced kriging method, used here only for $\overline{V}_{S30}$ and $\overline{V}_{S50}$ due to the fact that for these the number of input values was more satisfactory. Prediction errors are depicted in figure 3 with grey lines; their intervals were chose using the mean geometric classification method. It is to be noted however that kriging modifies the values around the input data, based on the computed statistics relying on a semi-variogram. Both IDW and kriging interpolation was performed using ESRI ArcMap version 10.6 with the geostatistical and spatial analyst toolboxes.

5. DISCUSSION

5.1. V_S MAP INTERPRETATION

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

For $\overline{V}_{S30}$ and $\overline{V}_{S50}$, figure 3 and figure 4 show that in the north-eastern part of the city there is an increase in the values; although expected, it seems that the presence of the Pipera swamp as well as the Colentina River does not influence this feature. Across the Dâmbovița River, on both sides, the values are minimum for $\overline{V}_{S30}$, up until the eastern part of the city. $\overline{V}_{S50}$ values appear to be more homogenized for the western and central part of the city. For the south-eastern part of the city, due to the lack of measurement points, the errors can be significant. Especially toward Arges river (10 km south of Bucharest), the V_S values are expected to be smaller in reality.

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

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

In the interpretation of the results, some other factors as geomorphological, geological and hydrogeological variations throughout the city need to be taken into consideration. As a trend, figure 4d shows a similar pattern with the topographic map in figure 1; lower $\overline{V}_S$ values correspond to the higher region of the city of 100–130 m altitude, while upper $\overline{V}_S$ values are distributed toward the south-east part, corresponding to lower region of the city (40–80 m altitude).

5.2. THE USE OF V_S IN SPECTRAL ACCELERATION MODELS COMPUTED BY EQUIVALENT LINEAR MODELLING METHOD

Different methods of ground response analysis have been developed including one dimensional, as well as 2D and 3D approaches. Various modelling techniques like the *finite element method* were implemented for linear and non-linear analysis. Extended information on these analyses is given in Kramer (1996). Here we apply an equivalent linear one-dimensional analysis, as implemented in the computer programs for the analysis of geotechnical earthquake engineering problems such SHAKE2000 (Ordonez 2012). The *static soil properties* required in the 1D ground response analysis with SHAKE2000 are: maximum shear wave velocity or maximum shear strength and unit weight. Since the analysis accounts for the non-linear behaviour of the soils using an iterative procedure, *dynamic soil properties* play an important role. The shear modulus reduction curves and damping curves are usually obtained from laboratory test data (cyclical triaxial soil tests). The 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 worldwide published geotechnical tests (Ordonez 2012). 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.

In the research performed in the last years the need for better data acquired by field measurements becomes a necessity and some studies have been made targeting the possibility of acquiring data employing new methods in the field, as well as in the laboratory, where the “field” is in our case a very big and populated city – Bucharest (Bălă *et al*., 2013).

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

1. The interval seismic velocities V_S (m/s) and mean velocity values weighted with the thickness of each layer will be used for V_S. The shear-wave velocity values will be measured in situ with special designed seismic methods. The thickness of each layer (m) will come from previous selected geologic models as well as the natural unit weight (kN/m3) measured on probes.

2. The shear modulus ratio curves and damping curves versus shear strain (γ) are used in the programs like *SHAKE2000* as built-in curves, although the program permitted the introduction of site-specific curves for a certain location. The engineering procedure requires that the curves will be either determined by measurements applied on the rock samples collected from boreholes drilled in Bucharest City at that time (Lungu *et al*., 1999). They were continued by Arion *et al*., (2006) and Arion *et al*., (2007), who presented the curves of G/G_0 and D/D_o for some samples of clays collected in Bucharest area and measured in laboratory conditions. Later measurements in the area of Bucharest are performed in the frame of NATO Science for Peace Project on samples extracted from principal layers during the digging of the 10 boreholes. The samples were measured in laboratory conditions by the group of UTCB (partners in the project), preserving the humidity of the probes, and the results in the form of G/G_0 and D/D_o were reported by Bălă *et al*., (2013).

3. The strong motion of the ground used as input can be a historic earthquake that has been recorded in the area, in order to reflect the characteristic period would have the arriving strong signal at the site. In theory strong signal should be recorded by a seismometer placed on the bedrock, because the modelling process assumes an input signal traveling from bedrock to surface level.

The engineering bedrock (EB) was proposed in Bucharest area at the upper limit of Frăţeşti A layer first by Lungu *et al*., (1999), for which shear-wave seismic velocities in the domain of 500–550 m/s were reported later by Bălă *et al*., (2007); Bălă *et al*., (2009a); Bălă *et al*., (2009b). One can observe that the proposed interface does not comply with any of the geotechnical requirements which are usually imposed for EB. In Eurocode 8 the shear-wave seismic velocities for the highest grade, type **A** soil, is fixed at 800 m/s, so the bedrock should have a higher velocity, usually by a jump in the values at EB interface.

Other researchers (Cioflan 2006) have documented the existence of EB at the upper limit of rocks with V_S = 1220–1600 m/s, while in the upper part should be rocks with at least 650 m/s. That means for Bucharest the interface between 500–1000 m depth, the boundary which separate the Cretaceous (V_S = 1200–1350 m/s) from Tertiary rocks (V_S = 600–650 m/s), see Bălă (2014).

In theory the interface that is considered the geophysical bedrock should be continuous, composed from a compact rock and extended horizontally under the area of interest: Bucharest city and surroundings. In fact, the local geological situation is much complex.

The Frăţeşti complex is composed of 3 principal layers of gravel which contains important aquifers, separated by layers of compact shale, which have obvious different thickness and heterogeneous characteristics depending on the site.

The upper interface of Frăţeşti layers is dipping from south to north, from 100 m depth at Măgurele (south-west of Bucharest) to about 200 m in Otopeni (north of Bucharest). So, the interface is not horizontal as it is assumed for the EB, but it has a certain gradient, dipping from 90–100 m depth in the south, to 150–160 m depth in the northern part of Bucharest.

After all these observations, supported by recent studies, it can be concluded that the EB cannot be fixed in the underground of Bucharest, 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 (Bălă 2014).

The average values of shear-wave velocities presented above in table 1 are generally very close, although they were measured by quite different seismic methods in boreholes, by penetration tests (SCPT), or at the surface in Bucharest (seismic refraction). The narrow range in which the mean shear-wave velocities for each of the geologic layer are placed, allows us to use them for the evaluation of mean values for each of the 7 Quaternary layers.

The average densities presented in table 1 are actual densities recorded after laboratory measurements in the NATO SfP Project 981882, the experiment including core sampling of the representative sedimentary layers and determining the geotechnical values for each layer under laboratory conditions Bălă *et al*., (2011).

7. CONCLUSIONS

In the present paper we gather and reinterpret in a new and necessary database V_S values measured through different methods, for Bucharest, the seismically endangered capital of Romania. All measurements are checked with the original sources and $\overline{V}_S$ values are recomputed in some cases, in order to homogenize results. $\overline{V}_S$ values are deduced for 4 fixed depth intervals: 30 m, 50 m, 70 m and 100 m and are used to generate relevant maps.

A main advantage of the database is that its V_S values are measured in situ and computed without any influence from subjective interpretation like the geological interpretation of lithological columns or establishing the limits of the 7 main geological complexes, across the city, like it was done until now.

The database provides evidence to support the distribution of seismic velocities in the Bucharest underground, but most importantly enables further modelling of local site amplification, with better reliability across the city. The main advantage of these maps is that one can design a full network of points at surface, in which the models of spectral acceleration peaks from any interface defined in the ground are to be computed. Given that the maps use a compilation of also newer measured points (compared to older versions such as the ones in Kienzle *et al*., 2006, Bălă *et al*., 2008 or Arion *et al*., 2012) and two interpolation methods reflecting however similar patterns, these can be considered the most relevant attempt to map V_S in Bucharest.

The models are designed to be used to continue the efforts towards a comprehensive microzonation of the Bucharest City by means of enhanced response spectra and transfer functions by equivalent linear modelling methods.

Data availability: The shear-wave velocity database for Bucharest can be retrieved from https://data.mendeley.com/datasets/jncnc6fng9 (Toma-Danila *et al*., 2021)

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REFERENCES

Aldea, A., Yamanaka, H., Negulescu, C., Kashima, T., Radoi, R., Kazama, H. & Călărașu, E., 2006. Extensive seismic instrumentation and geophyiscal investigation for site-response studies in Bucharest, Romania, in *Proceedings of the Third International Symposium on the Effects of Surface geology on Seismic Motion*, Grenoble, France, paper no. 69.

Aldea, A., Poiata, N., Kashima, T., Albota, E. & Demetriu, S., 2007. NCSRR Digital Seismic Network in Romania, in *Proceedings of the International Symposium on Seismic Risk Reduction*, The JICA Technical Cooperation Project in Romania, 143–156.

Arion, C. & Neagu, C., 2006. Laboratory investigation for estimation of seismic response of the ground, in *Proceedings of 1st European Conference on Earthquake Engineering and Seismology*, Geneva, Switzerland, paper no. 519.

Arion, C. & Neagu, C., 2007. Laboratory investigation for estimation of seismic response of the ground, in *Proceedings of the International Symposium on Strong Vrancea Earthquakes and Risk Mitigation*, Bucharest, Romania, 222–225.

Arion, C., Neagu, C., Văcareanu, R. & Călărașu, E., 2012. In Situ Investigation for Microzonation of Bucharest Surface Geology, in *Proceedings of the 15th World Conference on Earthquake Engineering*, Lisbon, Portugal, paper no. 2034.

Bălă, A., Raileanu, V., Zihan, I., Ciugudean, V. & Grecu, B., 2006. Physical and dynamic properties of the shallow sedimentary rocks in the Bucharest Metropolitan Area, *Romanian Reports in Physics*, **58**, 221–250.

Bălă, A., Ritter, J.R.R., Hannich, D., Balan, S.F. & Arion, C., 2007. Local site effects based on in situ measurements in Bucharest City, Romania, in *Proceedings of the International symposium on Seismic Risk Reduction*, Bucharest, Romania, 367–374.

Bălă, A., Balan, S.F., Ritter, J.R.R., Hannich, D., Huber, G. & Rohn, J., 2007. Seismic site effects based on in situ borehole measurements in Bucharest, Romania, in *Proceedings of the International Symposium on Strong Vrancea Earthquake and risk mitigation*, Bucharest, Romania, 190–204.

Bălă, A., Zihan, I., Ciugudean, V., Raileanu, V. & Grecu, B., 2008. Physical and dynamic properties of the Quaternary sedimentary layers in and around Bucharest City, *Romanian Reports in Physics*, **60**, 389–401

Bălă, A., Aldea, A., Hannich, D., Ehret, D. & Raileanu, V., 2009a. Methods to assess the site effects based on in situ measurements in Bucharest City, Romania, *Romanian Reports in Physics*, **1**, 335–346.

Bălă, A., Grecu, B., Ciugudean, V. & Raileanu, V., 2009b. Dynamic properties of the Quaternary sedimentary rocks and their influence on seismic site effects. Case study in Bucharest City, Romania, *Soil Dynamics and Earthquake Engineering*, **29**, 144–154.

Bălă, A., Balan, S.F., Ritter, J.R.R., Rohn, J., Huber, G. & Hannich, D., 2010. *Site-effect analyses for the earthquake-endangered metropolis Bucharest, Romania*, Alexandru Ioan Cuza Univ. Ed., Iasi, Romania.

Bălă, A., Hannich, D., Ritter, J.R.R. & Ciugudean-Toma, V., 2011. Geological and Geophysical Model of the Quaternary Layers based on in situ measurements in Bucharest, Romania, *Romanian Reports in Physics*, **63**, 250–274.

Bălă, A., Arion. C. & Aldea, A., 2013. In situ borehole measurements and laboratory measurements as primary tools for the assessment of the seismic site effects, *Romanian Reports in Physics*, **65**, 285–298.

Bălă, A., 2014. Quantitative modelling of seismic site amplification in an earthquake-endangered capital city: Bucharest, Romania, *Natural Hazards*, **72**, 1429–1445.

Bălă, A. & Hannich, D., 2021. Liquefaction potential analysis in Bucharest City as a result of the ground shaking during strong Vrancea earthquakes, *Athens Journal of Technology and Engineering*, **8**, 113–138.

Călărașu, E.-A., Arion, C. & Neagu, C., 2018. Geo-data modelling an engineering tool as guidelines for estimating near-surface seismic effects, in *Proceedings of the 16th European Conference on Earthquake Engineering*, Thessaloniki, Greece.

Cioflan, C.O., 2006. *Efecte seismice locale*, Alexandru Ioan Cuza Univ. Ed., Iasi, Romania.

Cioflan, C. O., Marmureanu, A. & Marmureanu, G., 2009. Nonlinearity in seismic site effects evaluation, *Romanian Journal of Physics*, **54**, 951–964.

Ciugudean-Toma, V. & Stefanescu, I., 2006. Engineering geology of the Bucharest city area, Romania, *IAEG Conference: Engineering Geology for tomorrow's cities*, Nottingham, United Kingdom, paper no. 235.

European Committee for Standardization, 2004. Eurocode 8 (EN 1998–1): Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings.

Ghazi, A., Moghadas, N.H., Sadeghi, H., Ghafoori, M. & Lashkaripour, G.R., 2014. Spatial Variability of Shear Wave Velocity Using Geostatistical Analysis in Mashhad City, NE Iran, *Open Journal of Geology*, **4**, 354–363.

Hannich, D., Huber, G., Ehret, D., Hoetzl, H., Balan, S., Bălă, A., Bretotean, M. & Ciugudean, V., 2006. SCPTU Techniques Used for shallow geologic/hydrogeologic Site Characterization in Bucharest, Romania, in *Proceedings of the 3rd International Symposium on the Effects of Surface Geology on Seismic Motion*, Grenoble, France, paper no. 71.

Hannich, D. & Orlowsky, D., 2014. Shear-wave velocities of the Quaternary layers determined by Multi-Offset Vertical Seismic profiling (MOVSP) in Bucharest, Romania, *Romanian Reports in Physics*, **66**, 1207–1225.

INCDFP, 2021. *Romplus earthquake catalogue*, http://www.infp.ro/index.php?i=romplus

Lăcătușu, R., Anastasiu, N., Popescu, M. & Enciu, P., 2007. Bucharest Municipality GEO-ATLAS. ESTFalia Ed., Bucharest, Romania (in Romanian)

Liteanu, G., 1952. Geology of the city of Bucharest. Technical Studies, Series E, *Hydrogeology*, **1** (in Romanian).

Lungu, D., Cornea, T., Aldea, A., Nedelcu, C. & Zaicenco, A., 1997. *Seismic microzonation of the city of Bucharest, Romania*, Technical Report for the Association Francaise de Genie Paraseismique, 1, 1–91.

Lungu, D., Aldea, A., Moldoveanu T., Ciugudean V., Stefanica M., 1999, Near-surface geology and dynamic properties of soil layers in Bucharest, in *Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation*, pp. 137–148, ed. Wenzel, F., Lungu, D. & Novak, O., Kluwer Academic Publishers.

Lungu, D. & Călărașu, E., 2005. Some aspects regarding seismic microzonation of the City of Bucharest, in *Proceedings of the International Conference "Earthquake Engineering in the 21st Century"*, Skopje, Macedonia.

Kienzle, A., Hannich, D., Wirth, W., Ehret, D., Rohn, J., Ciugudean, V. & Czurda, K., 2006. A GIS-based study of earthquake hazard as a tool for the microzonation of Bucharest, *Engineering Geology*, **87**, 13–32.

Manea, E., Clotaire, M., Poggi, V., Fäh, D., Radulian, M. & Balan, S., 2016. Improving the shear wave velocity structure beneath Bucharest (Romania) using ambient vibrations, *Geophysical Journal International*, **207**, 848–861.

Manea, E.F., Michel, C., Hobiger, M., Fah, D., Cioflan, C.O & Radulian, M., 2017. Analysis of the seismic wavefield in the Moesian Platform (Bucharest area) for hazard assessment purposes, *Geophysical Journal International*, **210**, 1609–1622.

Mărmureanu, G., Mărmureanu, A., Manea, E.F., Toma-Danila, D., Vlad, M., 2016. Can we use more classic seismic hazard analysis to strong and deep Vrancea earthquakes?, *Romanian Journal of Physics*, **61**, 728–738.

Mărmureanu, G., Cioflan, C.O. & Mărmureanu, A., 2010. *Cercetari privind hazardul seismic local (microzonare) a zonei metropolitan București*, Technopress Ed. (in Romanian), Iasi, Romania.

Neagu, C., Arion, C., Aldea, A., Călărașu, E.-A., Văcăreanu, R. & Pavel, F., 2018. Ground Types for Seismic Design in Romania, in Seismic Hazard and Risk Assessment: Updated Overview with Emphasis on Romania, pp. 157–172, ed. Văcăreanu, R. & Ionescu, C., Springer Nature.

Ordonez, G.A., 2012. *SHAKE2000: A computer program for the 1-D analysis of geotechnical earthquake engineering problems*, GeoMotions LLC, Lacey, Washington, USA.

Orlowski, D., Witte, C. & Loske, B., 2003. *Execution and evaluation of seismic measurements in Bucharest by the Multi-Offset-Vertical-Seismic-Profiling method (MOVSP)*. Internal Report, DMT, Mines & More Division, Essen (in German).

Raileanu, V., Bălă, A., Hauser, F., Prodehl, C. & Fielitz, W., 2005. Crustal properties from S wave and gravity data along a seismic refraction profile in Romania, *Tectonophysics*, **410**, 251–272.

Sebe, O., Forbriger, T., Ritter, J.R.R., 2009. The shear wave velocity underneath Bucharest city, Romania, from the analysis of Love waves, *Geophysical Journal International*, **176**, 965–979.

Sun, C.G. & Kim, H.S., 2017. GIS-based regional assessment of seismic site effects considering the spatial uncertainty of site-specific geotechnical characteristics in coastal and inland urban areas, *Geomatics, Natural Hazards and Risk*, **8**, 1947–1621.

Thitimakorn, T., 2013. Development of a NEHRP site classification map of Chiang Mai city, Thailand, based on shear-wave velocity using the MASW technique, *Journal of Geophysics and Engineering*, **10**, 045007.

Toma-Danila, D., Bălă, A. & Arion, C., 2021. *Shear-wave velocity database for Bucharest*, Mendeley Data, doi: 10.17632/jncnc6fng9, https://data.mendeley.com/datasets/jncnc6fng9

Toma-Danila, D. & Armaș, I., 2017. Insights into the possible seismic damage of residential buildings in Bucharest, Romania, at neighborhood resolution, *Bulletin of Earthquake Engineering*, **15**, 1161–1184.

UTCB, 2013. *Romanian Seismic Design Code P100–1/2013*

vonSteht, M., Jaskolla, B. & Ritter, J.R.R., 2008. Near surface shear wave velocity in Bucharest, Romania, *Natural Hazards and Earth System Science*, **8**, 1299–1307.

Wald, D.J. & Allen, T.I., 2007. Topographic slope as a proxy for seismic site conditions and amplification, *Bulletin of the Seismological Society of America*, **97**, 1379–1395.

Yaghmaei-Sabegh, S. & Rupakhety, R., 2020. A new method of seismic site classification using HVSR curves: A case study of the 12 November 2017 Mw 7.3 Ezgeleh earthquake in Iran, *Engineering Geology*, **270**, paper no. 105574.

Yordkayhun, S., Sujitapan, C. & Chalermyanont, T., 2015. Shear wave velocity mapping of Hat Yai district, southern Thailand: implication for seismic site classification, *Journal of Geophysics and Engineering*, **12**, 57–69.