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PHYSICAL AND DYNAMIC PROPERTIES OF THE SHALLOW SEDIMENTARY ROCKS IN THE BUCHAREST METROPOLITAN AREA

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Abstract. New seismic measurements are performed in the Bucharest area with the purpose of defining better the physical and dynamic properties of the shallow sedimentary rocks. Down-hole seismic measurements were performed in a number of 10 cased boreholes drilled in the Bucharest metropolitan area. Processing and interpretation of the data lead to the conclusion that shallow sedimentary rocks can be considered weak in the area, down to 150–200 m depth. Seismic wave velocity values and bulk density values presented in the paper associated with local geology are useful primary data in the seismic microzonation of Bucharest City. They are used as 1D models to derive transfer functions and response spectra for the stack of sedimentary rocks in several parts of the Bucharest area, leading to a better knowledge of the local site amplification and associated frequency spectra.

Key words: down-hole seismic measurements, site amplification, acceleration response spectra, seismic microzonation.

1. DOWN-HOLE SEISMIC MEASUREMENTS

Down-hole seismic measurements were performed by a combined effort of the National Institute for Earth Physics (NIEP) and SC "Prospectiuni" S.A. in 10 new locations (boreholes) which are presented in Table 1.

The locations of the boreholes, as well as the position of two boreholes (Centura 1 and Centura 2) previously measured (Bala *et al.*, 2005), are presented in the Fig. 1.

The boreholes were protected with plastic tubes and/or steel tubes and seismic measurements are performed down to the bottom of each borehole.

The shot point was fixed at 10–30 m from the borehole, depending on the local conditions in the field. Wave generation was performed by hammer blows on a wooden block. A seismic station type-DAQLink -24, with 24 channels (24 bits) was

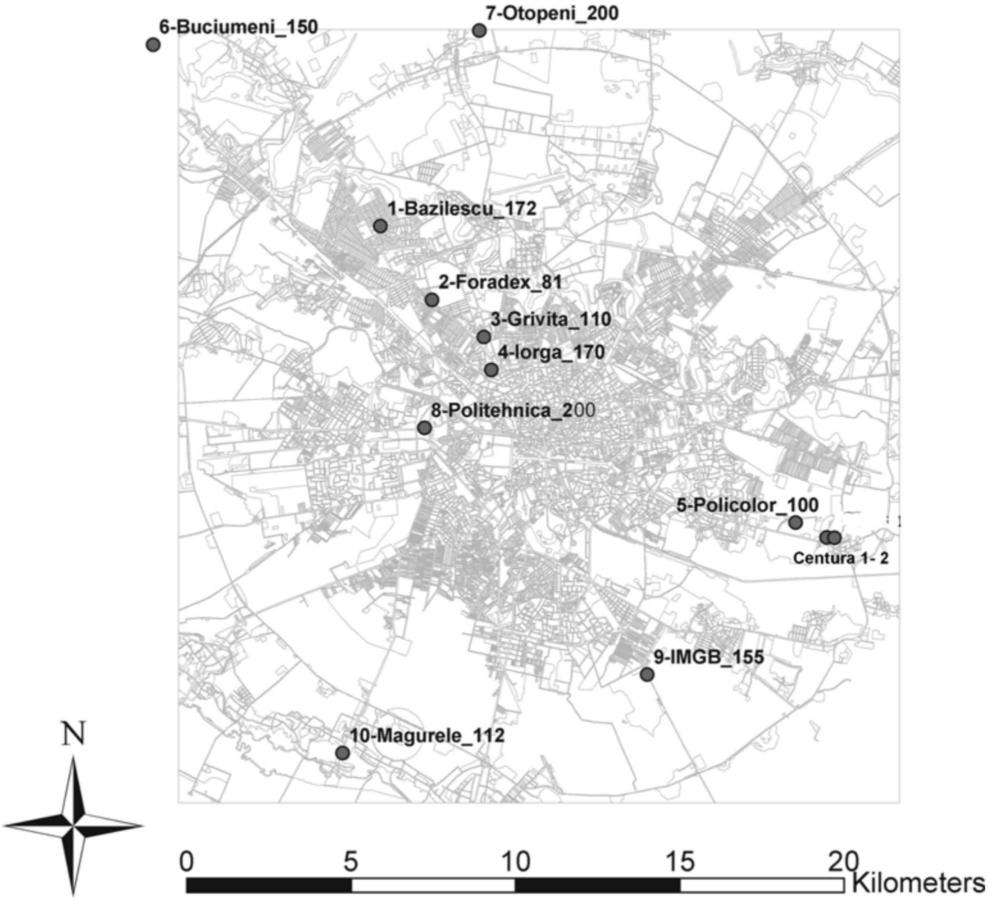

Fig. 1 – Position of the boreholes from Table 1, in which down-hole seismic measurements were performed. The circular contour delimits the Bucharest City area.

employed, with a sampling rate of 1 ms. The time length of each recording was 1 s. A three component sensor clamped on the borehole wall was used for recording, with a recording offset of 1 m until 70 m depth and an offset of 2 m below this depth.

P wave onset was read on the vertical component and for the S wave the horizontal components of the sensor were used. Time and frequency criteria were used to correlate the S waves. Separate arrival times *vs.* depth graphs were constructed for P and S waves.

Interval seismic velocities Vp and Vs are presented in Fig. 2 for the 4 boreholes noted with (*) in Table 1. Detailed geologic data and geophysical values from *in situ* measurements for 5 boreholes are presented in Annex 1 (Tables 7–11).

Density values and lithological columns are provided by SC METROUL SA from detailed *in situ* and laboratory measurements for the Politehnica and IMGB

Table 1

The new locations for down-hole seismic velocity measurements in Bucharest

No	Borehole	Depth [m]	Latitude [degrees]	Longitude [degrees]	Administrator
1.	Bazilescu_172	172	44.49	26.04	ADP, sector 5
2.	Foradex_81	81	44.47	26.06	FORADEX S.A.
3.	Grivita_110	110	44.46	26.08	METROUL S.A.
4.	Iorga_170	170	44.451	26.083	METROUL S.A.
5.	Policolor_100	100	44.41	26.20	METROUL S.A.
6.	Buciumeni_150	150	44.539	25.952	PROSPECTIUNI S.A.
7.	Otopeni_200*	200	44.55	26.10	FORADEX S.A.
8.	Politehnica_200*	200	44.446	26.090	METROUL S.A.
9.	IMGB_156*	155	44.355	26.203	METROUL S.A.
10.	Magurele_112*	112	44.348	26.028	NIEP

boreholes, as well as for other boreholes in their administration (Table 1). For the other boreholes density values are inferred from the lithological columns available.

In the northern part of Bucharest (Otopeni area) Vp velocities are increasing from 500 m/s to 2250 m/s and Vs from 200 m/s to 611 m/s. Some inversions of the velocity values in depth are observed (Fig. 2).

In the southern part of Bucharest (Magurele and IMGB locations) Vp = 960 m/s–2300 m/s and Vs = 260–588 m/s. Frequent velocity inversions are present for both Vp and Vs, especially in the IMGB borehole. An unusual high Vs velocity of 833 m/s is recorded in the IMGB borehole at 145–155 m depth (Fig. 2).

In the central part (Politehnica borehole) Vp is increasing gradually from 833 m/s to 2800 m/s (at 60 m depth). Frequent velocity inversions are encountered for greater depths. Vs velocities are increasing from 227 m/s to 612 m/s, with some inversions in the shallow part (Fig. 2).

The Vp and Vs seismic velocities are in the same range as seismic velocities presented by Bala *et al.*, 2005 for 2 boreholes in the eastern margin of Bucharest City – Centura 1 and Centura 2 in Fig. 1.

The ratio Vs/Vp and Poisson's ratio were computed and represented in Fig. 3 for each of the boreholes from Fig. 2.

Computed Poisson ratios range from 0.375 in the shallow part (above the water level) and 0.43–0.49 in the depth. At the base of the boreholes values of 0.41–0.45 are encountered (Fig. 3). A special discussion is worth having on the Poisson ratio values of 0.49.

Field tests have indicated Poisson ratio values between 0.25 and 0.5, above which the rock becomes plastic, *i.e., the stresses are equal in all directions* (Weurker,1963). Poisson's ratio varies with both rock type and the degree of compaction, but it will never exceed 0.5. Every rock will have its own characteristic

Poisson's ratio. A note should be made of unconsolidated clay formations, often found at shallow depths wells, which may exhibit abnormally high fracture

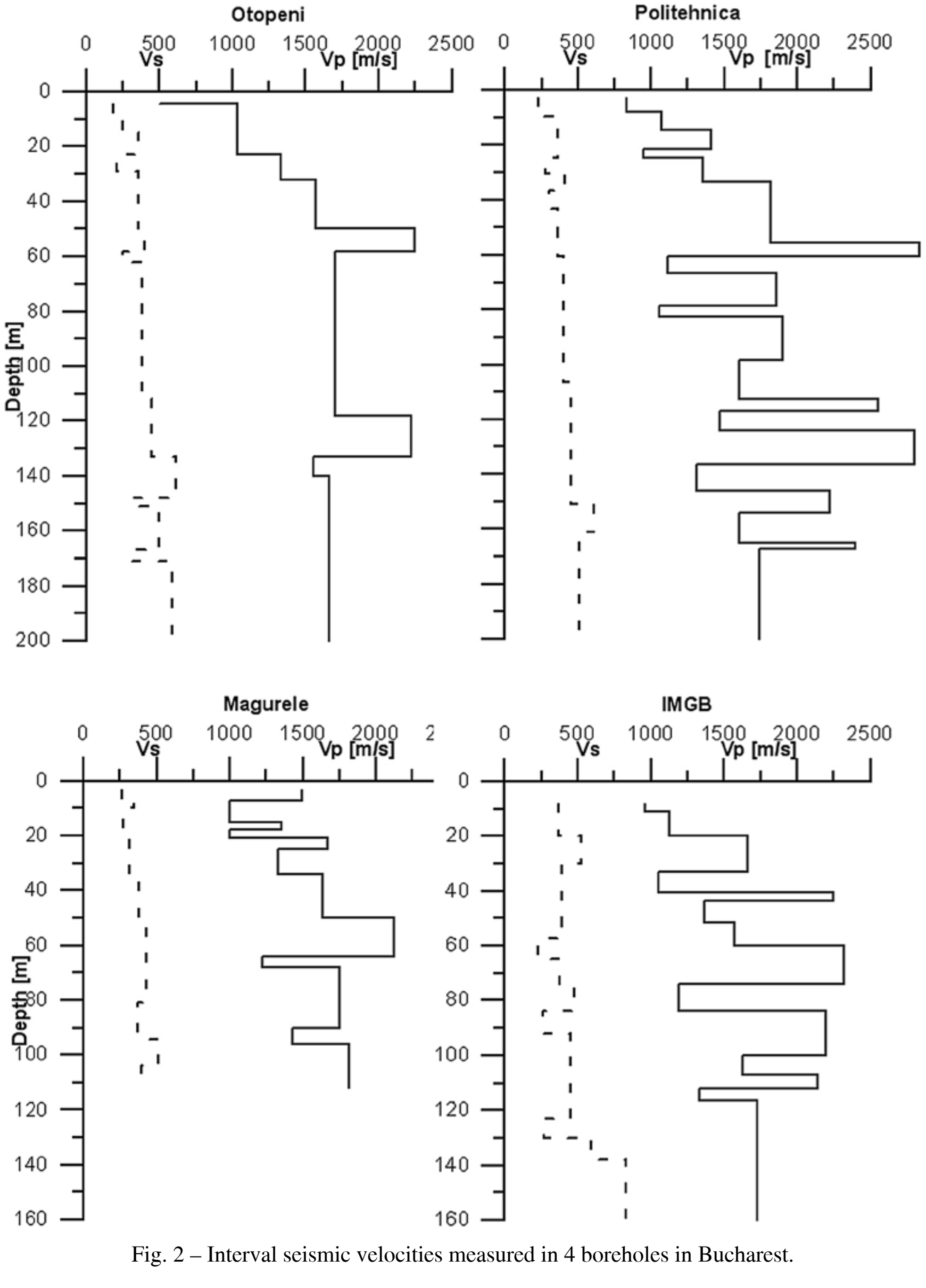

Fig. 2 – Interval seismic velocities measured in 4 boreholes in Bucharest.

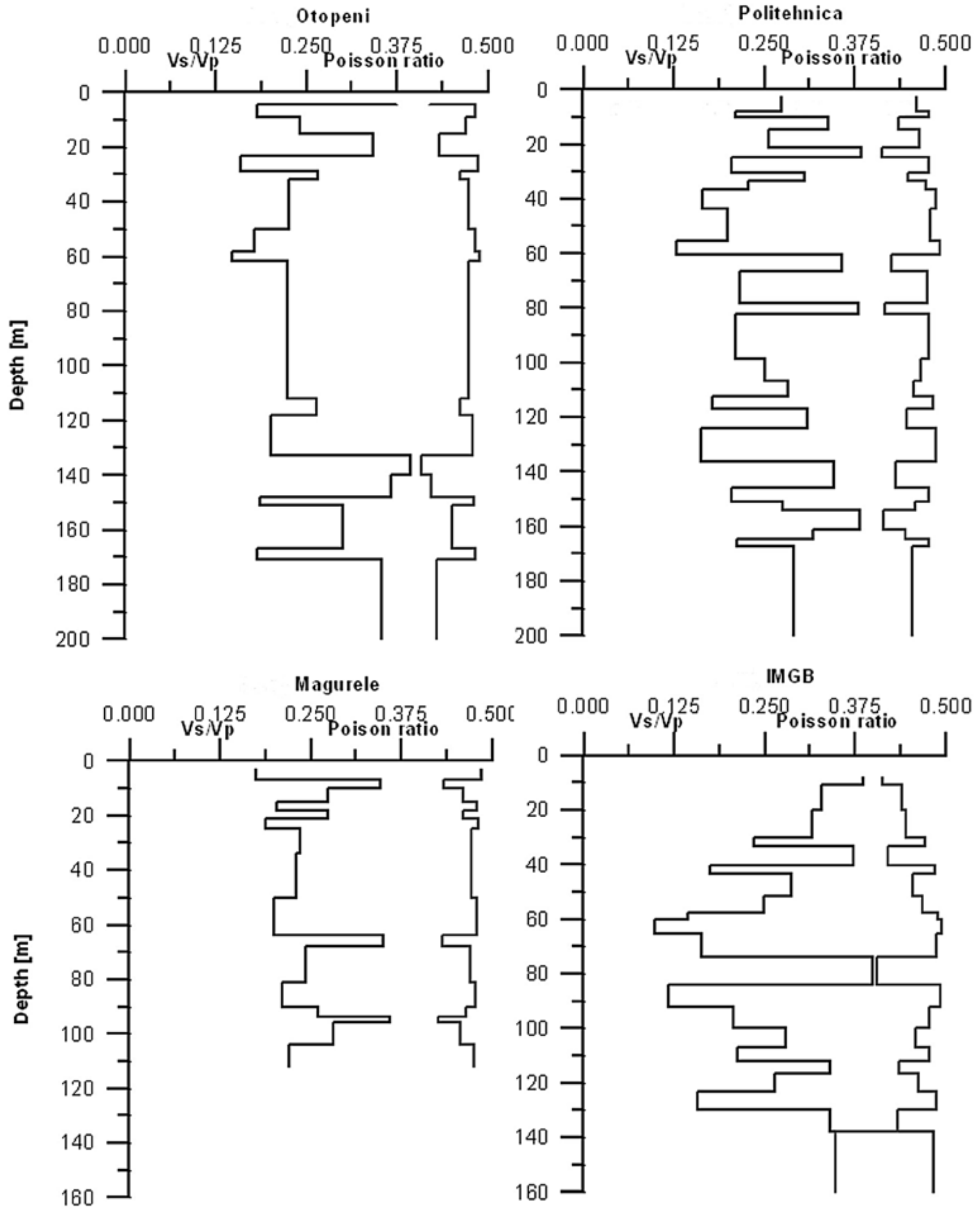

Fig. 3 – Vs/Vp and Poisson ratio computed for 4 boreholes in Bucharest area.

pressures. Wet clays will behave plastically and the Poisson’s ratio will approach 0.5. Due to the pore water and adsorbed water surrounding the individual clay platelets, these platelets will not be in contact with each other, and so these clay types will have very low shear strength. Thus the pore water would be supporting the weight of the overlying sediments and the pore pressure should almost be equal to the overburden pressure. With increased depth, compaction will squeeze out some of the pore water, bringing the clay platelets into contact. They are then able to support a superimposed horizontal stress, and Poisson's ratio will become similar to that of a more compact clay.

Some values of Poisson ratio found by measurements in sedimentary rocks are presented in Table 2.

Table 2

Suggested values of Poisson's Ratio for some sedimentary rocks (From Weurker R. G. "Annotated Tables of Strength & Elastic Properties of rocks", Drilling Reprint Series SPE, Dallas, 1963)

Formation type	Poisson's ratio
clay, very wet	0.50
clay	0.17
conglomerate	0.20
dolomite	0.21
greywacke:	
coarse	0.07
fine	0.23
medium	0.24
limestone:	
fine, micritic	0.28
medium, calcarenitic	0.31
porous	0.20
stylolitic	0.27
fossiliferous	0.09
bedded fossils	0.17
shaly	0.17
sandstone:	
coarse	0.05
coarse, cemented	0.10
fine	0.03
very fine	0.04
medium	0.06
poorly sorted, shaly	0.24
fossiliferous	0.01
shale	
calacareous (< 50% $CaCO_3$)	0.14
dolomitic	0.28
siliceous	0.12
silty (< 70% silt)	0.17
sandy (< 70% sand)	0.12
kerogenaceous	0.25
siltstone	0.08
slate	0.13
tuff (glass)	0.34

In Fig. 4 the relation Vs/Vp is presented for the 4 boreholes in which down-hole seismic measurements are performed in the Bucharest area. The interval seismic velocities have some dispersion, but they generally cover the same area. Greater values are observed in the IMGB and Politehnica boreholes due to the increased velocity values in depth (triangles and dots in Fig. 4). An unexpected value is recorded in the IMGB borehole due to a Vs value of 833 m/s at 150–156 m depth.

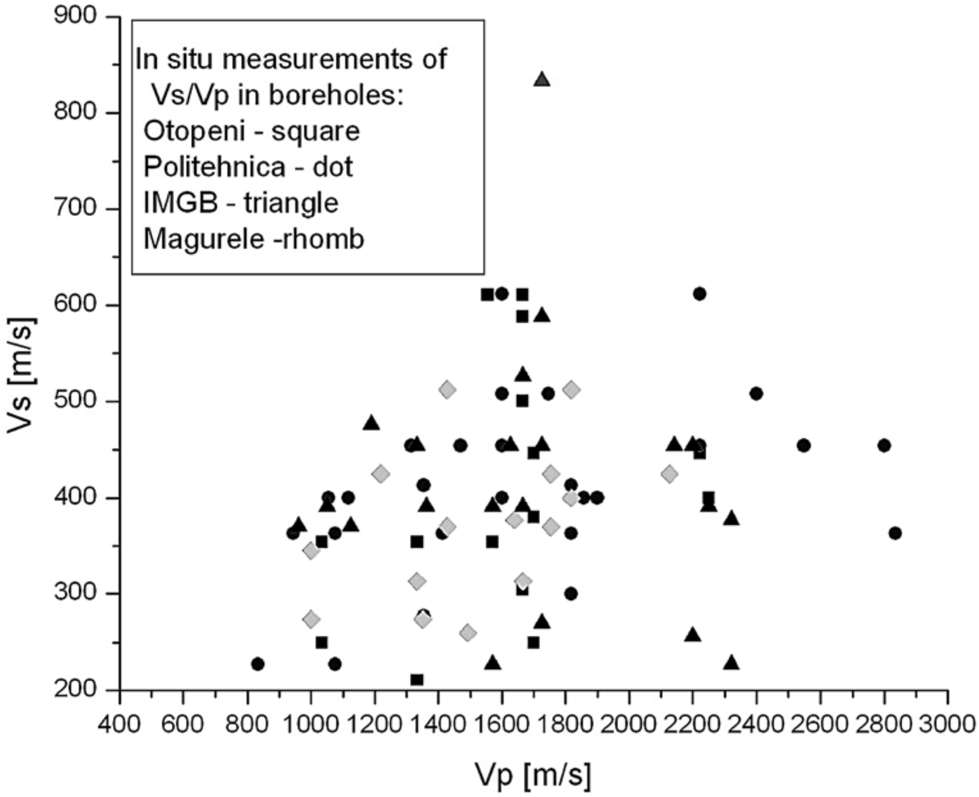

Fig. 4 – Vs to Vp relation in the 4 boreholes in Bucharest area.

2. TECHNICAL PARAMETERS OF THE DOWN-HOLE SEISMIC MEASUREMENTS IN BOREHOLES

RECORDING CHAIN

- DAQLink – 24 seismic station, 24 bits, 24 channels
- Triaxial geophones with clamping device: 3 components
- Mechanical hammer with a force of up to 10 kN blowing on a wooden block

SEISMIC WAVES GENERATION

The wooden block was placed at an angle of 15–20° in respect of the horizontal direction in order to generate simultaneously both P and S waves. For each recording point at least 3 blows were recorded by summation, the number increasing to 5–7 blows in depth.

The quality of the seismograms is analyzed on the recording site and noisy seismograms were rejected from the summation process.

PROCESSING OF THE SIGNAL AND PROCEDURES TO ENHANCE THE SIGNAL/NOISE RATIO

All the seismograms resulted from the summation process were gathered by order of depth in a single wave table. The time picking for the P and S waves were done on filtered seismograms, on a minimum or a maximum phase. Tube waves were put into evidence on some seismograms with a velocity greater than that of P waves.

On unfiltered seismograms, with good signals, the zero phases were correlated and picked times from other phases were reduced to these zero phase pickings (see Figs. 5 and 6).

Time pickings for the P wave were less affected by seismic noise (natural or man-made), but time pickings for the S waves were affected by the interference with later arrivals of the P wave, by primary and/or multiple reflections, diffractions. Due to the fact that S waves have a lower frequency band, a low-pass filtering with cut-off frequency of 40 Hz considerably improved the signal/noise ratio for these type of waves (Figs. 10 and 11).

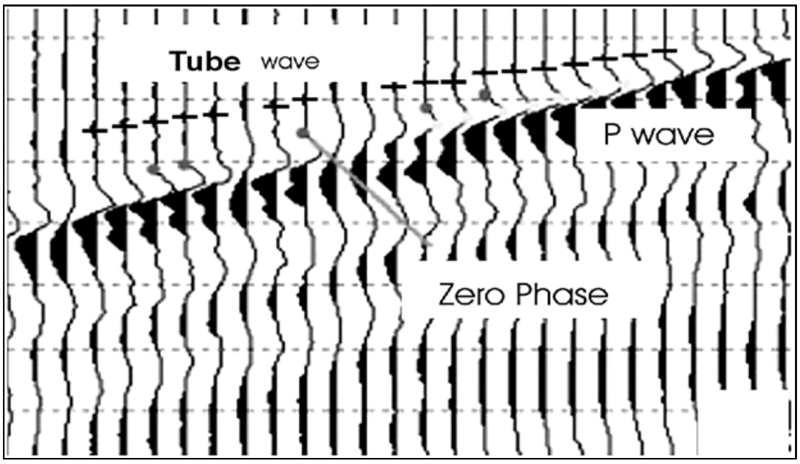

Fig. 5 – Zero phase and picked phase for the P wave.

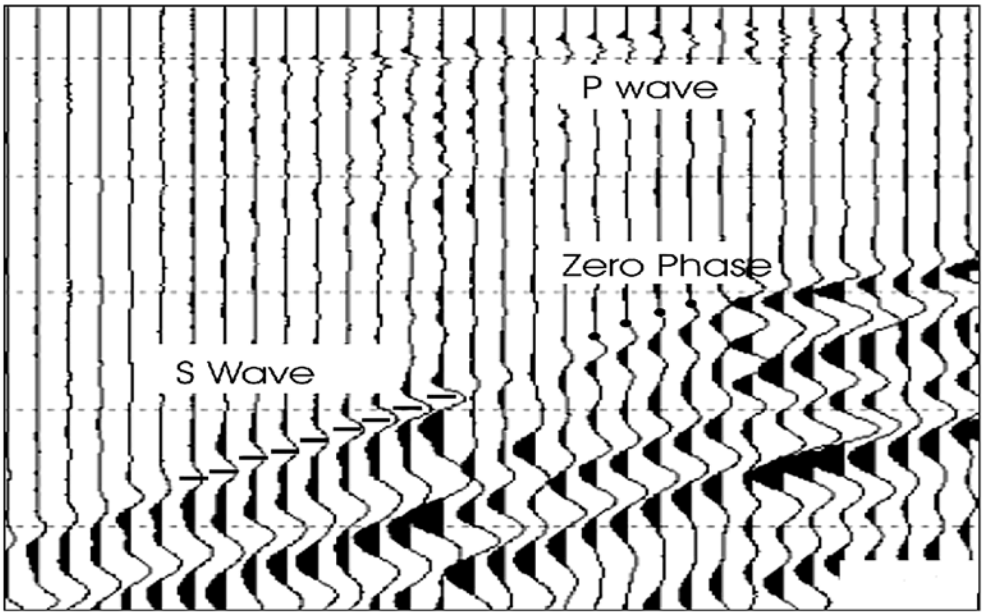

Fig. 6 – Zero phase and picked phases for the S wave.

Corrections were applied for the time picking due to the fact that the offset distance between borehole–source point was 20–30 m. These corrections were computed by multiplying the picked times with the cosine of the angle between the borehole direction (vertical) and the source point-recording point direction (Fig. 7).

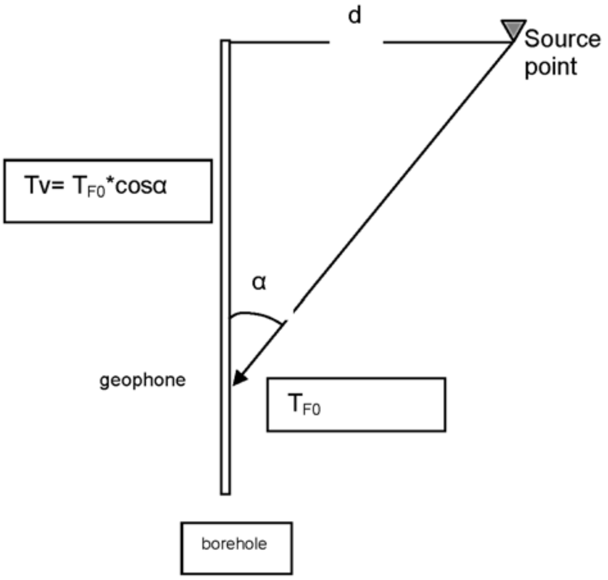

Fig. 7 – The geometry of the downhole seismic recordings.

Due to greater offset distances between the source point and the borehole, for shallow depths, the first arrival may represent the refraction wave on a near-surface limit for both P and S waves. In consequence the first P and S derived velocity is subject to some errors. Besides, in the boreholes belonging to SC "Metroul" SA, the first 6–10 m could not be used as the borehole crosses some empty chambers and/or concrete structures.

On Fig. 8 the effect of the summation on the noise is observed: the maximum noise level is lowered from 25% to 15% in the case of the P wave.

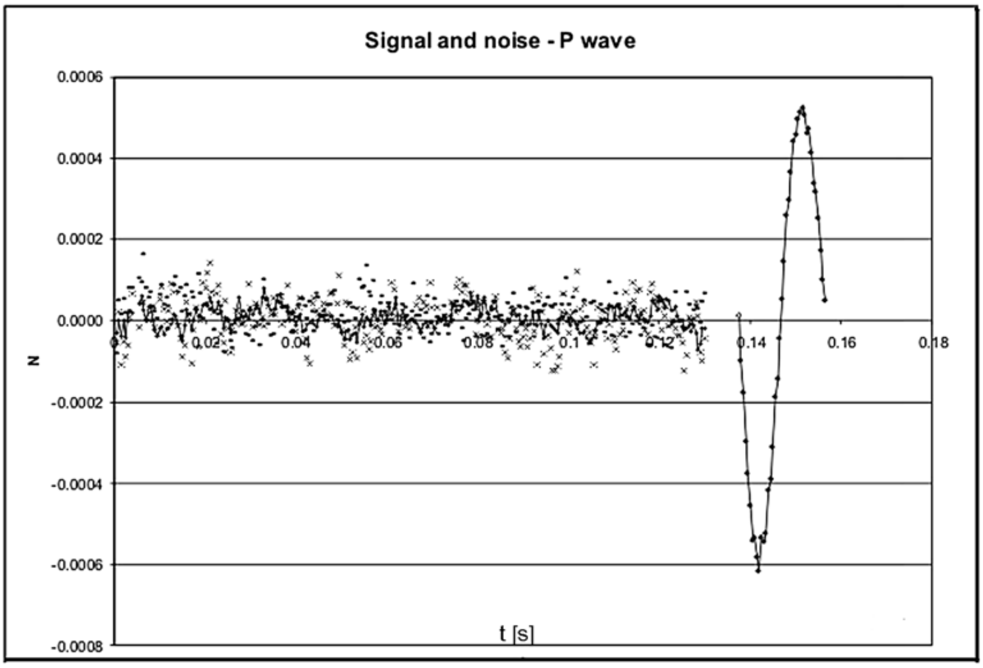

Fig. 8 – Graph of the summation of the P waves, the noise recorded on 3 channels and the summation of the noise.

The noise level of 15% can, however, modify the position of the signal maximum, moving it by about 1 ms. Therefore, deriving the seismic velocity in strata of 1–2 m thickness is subject to errors, especially in the case of greater velocities, where the time picking error is in the same range with the crossing time on the considered interval. To minimize this effect on the points of h(t) graphs, the medium values of several points were selected and represented by a line (Fig. 8).

In the case of the S waves the signal/noise ratio is lower and the noise may represent, even after the summation of 7 recordings, up to 50% from the signal (Fig. 9). Using low-pass filtering the signal/noise ratio was considerably improved (see Figs. 10 and 11).

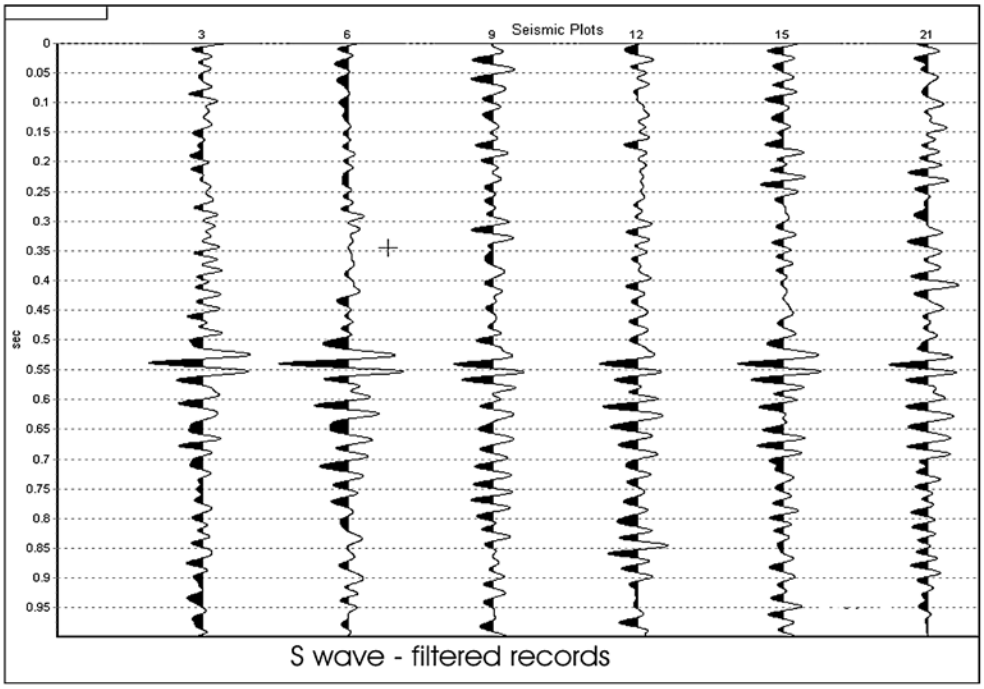

Fig. 11 – Low-pass filtered recordings (40 Hz) for the S wave.

QUALITY OF SEISMIC RECORDINGS

An example of a trace collection is given in Fig. 12 for the Otopeni borehole for 2 horizontal and 1 vertical components. The recordings are of good quality as well as in other sites in Bucharest. In some sites either channel 2 or channel 3 is used to compute S wave velocity, depending on the quality of the signal (IMGB borehole).

Vs and Vp interval seismic velocities were determined using the procedures presented above. The velocity values from the Otopeni borehole are given in Fig. 13.

3. GROUND RESPONSE ANALYSIS IN 5 SITES OF BUCHAREST AREA

The methods of one-dimensional ground response analysis are useful for level or gently sloping sites with parallel layer boundaries. Such conditions are common in the Bucharest area and one-dimensional analyses can be used in geotechnical earthquake practice. The earliest software written that uses this principle

is called: SHAKE. The computer program SHAKE was written in 1970–1971 by Schnabel and Lysmer (Schnabel *et al.*, 1972). This has been by far the most widely used program for computing seismic response of horizontally layered soil deposits. Other software that are derived from this basic code or based on the same principle are: Shake91 (Idriss and Sun, 1992); Shakedit; ProSHAKE (ProShake, 1999); SHAKE 2000.

The principle of one-dimensional ground response analysis is based on the assumption that all boundaries are horizontal and soil and bedrock are assumed *to extend infinitely in the horizontal direction* (half-sphere). The second assumption is that inclined incoming seismic rays are reflected to a nearly vertical direction, because of the decrease in velocities of the surface deposits. Therefore the response of the soil deposit is caused by shear waves propagating *vertically* from the underlying bedrock.

A so-called Transfer Function is used as a technique for 1D ground response analysis. Here the time history of the bedrock (input) motion is in the frequency domain represented as a Fourier Series using Fourier transform. Each term in the Fourier series is subsequently multiplied by the Transfer Function. The surface (output) motion is then expressed in the time domain using the inverse Fourier transform. The complex transfer function is however only valid for linear behaviour of soils. Therefore this approach has to be modified to account for the non-linearity.

The linear approach assumes that shear strength (G) and damping (ξ) are constant. However, the non-linear behaviour of soils is well known and can be determined very well in a laboratory environment. Shear strength reduces with increasing shear strain, while damping increases with increasing shear strain. These relationships can be tested and plotted in curves, called *shear modulus reduction curves* and *damping curves*, respectively. The problem then reduces to determining the equivalent values consistent with the level of strain induced in each layer. This is achieved using an iterative procedure on the basis of these curves (Idriss and Sun, 1992).

The program EDUSHAKE was employed to compute spectral acceleration functions at specific depths and transfer functions for the 1D models obtained for specific sites in Bucharest. This program was chosen because it represents a new version of the well known program SHAKE91, largely used by geoscientists in seismic microzonation studies (Idriss and Sun, 1992). It si also a free version of PROSHAKE program, for education and research purposes.

Acceleration response spectra computed by program EDUSHAKE correspond to the amplification due to the package of sedimentary layers, from 100 m depth (where bedrock was considered) up to the surface, that are expected to occur in the case of a moderate earthquake motion applied at the bottom of each 1D model (User Manual, PROSHAKE, version1.1).

INPUT DATA

The *static soil properties* required in the 1D ground response analysis with EDUSHAKE 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). Since the variation in geotechnical properties of the individual soil layers are mostly impossible to model, because of the shear lack of data, these properties 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 the program EDUSHAKE based on geotechnical tests published (User Manual, PROSHAKE, version1.1). A recent study (Aldea and Arion, 2001) shows that computed shear modulus reduction curves and damping curves for the shale samples obtained from GEOTEC 3 borehole (INCERC site) have their values in the same range as those presented by Vutecic and Dobry, 1991 and implemented in PROSHAKE.

As input data the interval seismic velocities Vs (in m/s), as well as the natural unit weight (in kN/m^3) and thickness of each layer (in m) are used. All these data were presented in Tables 7–11 of Annex 1 for 5 sites in the Bucharest area.

The *ground motion* can be a historic earthquake that has been recorded in the area, in order to reflect the characteristics it would have when arriving at the site. The seismogram would have to be recorded by a seismometer situated in bedrock, because the simulation assumes an input signal from bedrock to surface level. Because of the lack of an outcropping bedrock in the Bucharest area, a seismic signal recorded in a borehole at 100 m depth is used. The seismic signal is considered the same for the entire study area.

The recorded motion of the 27.10.2004 earthquake ($Mw = 6$) at K2 accelerometer station BBI is used as seismic input motion. All 3 components (one vertical and two horizontal components) were available. This station is placed in the borehole at the INCERC site at 100 m depth. The strong motion BBI_E was chosen because it has the largest acceleration from the 3 components and also it is a real recording of a Vrancea earthquake in the Bucharest area.

PROGRAM RESULTS

Examples of acceleration response spectra computed by the program EDUSHAKE are presented in Fig. 14.

A moderate amplification is present for the IMGB, Magurele and Otopeni sites following the general trend of acceleration response spectra of the original strong motion applied as input motion.

For the Policolor site a strong amplification occurs at 0.1 s (from 0.04 g to 0.11g), then the response spectra is decreasing toward 0.3 s (0.05 g).

For the Politehnica site we have also a significant increase in the acceleration response spectra: from 0.6 g at 0.1 s, to 0.8 g between 0.1–0.3 s and with a peak of 0.12 g at 0.6 s.

The graphs in Fig. 14 shows that 2 times and even 3 times amplification of the seismic signal can occur locally in Bucharest on account of the specific geological layers in some sites.

4. CONCLUSIONS FOR THE PHYSICAL PARAMETERS OF THE SEDIMENTARY ROCKS IN BUCHAREST

The geology of Bucharest City is characterized by 7 distinct sedimentary complexes, with different peculiarities and large intervals of thicknesses. Those shallow Quaternary complexes were first identified and separated by Liteanu (1951) and then cited by different authors with minor changes (Lungu *et al.*, 1999; Aldea and Arion, 2001; Ciugudean and Stefanescu, 2005; Hannich *et al.*, 2005).

Type 1 stratum: **Recent Surface Sediments**, made up of vegetal soil and clayey sediments, with a thickness locally reaching 15 m.

Type 2 stratum: **Upper Sandy-Clayey Complex**, is constituted of loess formations, often moisture sensitive, with sand layers and overall thickness of 16 m in the north and less than 1 m on the river side.

Researching the structure of these deposits, we remark the presence of two types: field deposits and meadow deposits different by thickness, structure and origin.

Type 3 stratum: **Colentina Gravel Complex**, made up of gravel and sand (with large variations in grain size) and frequently with water bearing, clayey layers, with a variable phreatic level from 1.5 m to 14.0 m. Thickness locally reaches 20 m. The specific average permeability coefficient of these aquifers is between 50 m to 250 m per day. From a genetic point of view, the crossing structure of gravels indicates very intense torrential conditions.

Type 4 stratum: **Intermediate Clay Complex**, made up of alternating brown and grey clays, with intercalation of hydrological fine confined sandy layers. The thickness of this layer reaches a 23 m maximum in the north of the city, but towards the south it becomes very thin and disappears. This stratum has disseminated limestone abundantly, limonite, and similitude with clays from the Lacustrine Complex, which leads to the conclusion that the origin is lacustrine.

Type 5 stratum: **Mostistea Sand Complex**, a confined water-bearing layer made up of fine grey sands with lenticular intercalation of clay. Its thickness varies from 10 m to 15 m and is continuously extending around Bucharest city.

Type 6 stratum: **Lacustrine Complex**, with thickness of 10–60 m, is made of clays and silty clays, with small lenticular sandy layers, most frequently situated at the top of this complex. The gray colour and also the limestone content show that the conditions are typical for a lacustrine facies.

Type 7 stratum: **Fratesti Sands Complex** is the deepest bearing stratum with a thickness of 100 m to 180 m and includes the A, B, C Fratesti levels. It is made up of sands and gravel, from which industrial and drinking water is usually pumped out (Ciugudean and Stefanescu, 2005).

The above types of strata were identified on each of the tables in Annex I from lithological columns. Weighted mean values for Vp and Vs are computed according to the following formula:

$$\overline{v}_s = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{v_{si}}} \qquad (1)$$

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 (NEHRP Recommended Provisions, 2000 Edition).

All these mean weighted seismic velocity values are presented in Table 3.

Table 3

Mean weighted seismic velocities for the 7 types of Quaternary layers in 5 sites from Bucharest area

Stratum type	1		2		3		4		5		6		7	
Mean weighted seismic velocity values [m/s]	Vp	Vs	Vp	Vs	Vp	Vs	Vp	Vs	Vp	Vs	Vp	Vs	Vp	Vs
Borehole Otopeni	500	187	1034	187	1034	250	1034	354	1333	354	1740	403	1666	523
Politehnica	–	–	833	227	1076	227	1211	335	1797	353	1731	444	1746	508
IMGB	–	–	–	–	960	370	1541	362	1541	362	1716	400	1725	628
Magurele	–	–	–	–	1492	260	1000	309	1413	325	1725	415	1818	512
Policolor	298	153	975	288	1140	284	1544	305	1544	305	1828	383	–	–

Seismic velocities are poorly represented or not at all in stratum types 1 and 2, due to the fact that they could be measured only in a few sites (Otopeni and Policolor sites). In stratum type 3 the velocities cover a fairly wide range 227–370 m/s, being represented by one or two layers in each borehole. Stratum types 4 and 5 have the same range of Vs velocities, between 305–362 m/s. In stratum type 6 most of the seismic velocities (Vs) are over 400 m/s: 383–444 m/s. Vs seismic velocities in stratum type 7 are in the range 508–523 m/s with an unusual large velocity of 628 m/s in the IMGB borehole. It should be noted that all these values are obtained by *in situ* measurements in Bucharest City area.

The seismic velocities given for the particular sites in Table 3 can be correlated with average Vs values cited from Ciugudean and Stefanescu, 2005.

For stratum types 2 and 3 it seems that average seismic velocities (234 m/s and 278 m/s) obtained in the present paper (Table 6) are lower than those of Lungu *et al.* (302 m/s and 335 m/s).

The values given in Table 4 after Hannich *et al.*, 2005 for average Vs seismic velocities in the stratum types 4 and 5 are a bit higher (by 8–12 %), while those for types 6 and 7 are in the same range as in the present study.

Table 4

Seismic share-wave velocity (Vs) / density model of the Quaternary sedimentary layers in Bucharest. After Ciugudean and Stefanescu, 2005; Hannich *et al.*, 2005.

Geologic layer no.	Depth of the upper limit of the geologic layer [m]	Average density [g/cm^3]	Average V_S [m/s]
1. Backfill	0	1.10	102 Lungu *et al.*,1999
2. Upper Clay Layer	0.50–5.00	1.75	302 Lungu *et al.*,1999
3. Colentina Aquifer (sand+gravel)	5.00–12.00	1.99	335 Lungu *et al.*,1999
4. Intermediate Clay Layer	10.00–20.00	2.07	378 Hannich *et al.*, 2005
5. Mostistea Aquifer (fine to medium sand)	15.00–30.00	2.00	400 Hannich *et al.*, 2005
6. Lacustrine Layer	35.00–50.00	2.14	442 Hannich *et al.*, 2005
7. Fratesti aquifer A (sand+gravel)	100.00-180.00	2.05	500 Hannich *et al.*, 2005

Another recent example of average values of share-wave seismic velocity is given by Lungu and Calarasu, 2005 in Table 5. They were computed with the same formula (1) for 7 sites in Bucharest, but for the depth interval from the ground surface down to two depth levels of 30 m and 60 m, respectively. Depending on the local geology, these depth levels correspond to layer no. 4 or layer no. 5. Because these values are mean weighted values at least for stratum types 1, 2, 3 and 4 at least, it is difficult to compare them directly with the mean values from Table 3. Mean weighted velocities $V_{S\text{-}30}$ and $V_{S\text{-}60}$ were computed for Otopeni, Politehnica and Policolor sites, with the same procedure as in the cited paper, and added at the end of the table for comparison. Their values are in the lower range and they correspond to those presented for INCERC 1 (70 m) and Basarab bridge (67 m).

Table 5

Average values of Vs for different sites in Bucharest (After Lungu and Calarasu, 2005)

Site location	Borehole depth	Vs – 30 m [m/s]	Vs – 60 m [m/s]
UTCB Plevnei	85	378	371
UTCB Tei	70	300	382
INCERC	70	218	352
INCERC	180	353	364
City Hall	67	360	371
Victory Square	152	314	360
Basarab bridge	67	253	284
Otopeni	*200*	*262*	*302*
Politehnica	*200*	*284*	*314*
Policolor	*100*	*265*	*284*

At present, the following classification is adopted by the National Earthquake Hazards Reduction Program, 2000 for SEISMIC REGULATIONS FOR NEW BUILDINGS AND OTHER STRUCTURES in the USA. The shear wave velocity near surface $V_{S\text{-}30}$ was used to divide the site types. They are: A type $V_S > 1\,500$ m/s; B type 750 ~ 1 500 m/s; C type 360 ~ 750 m/s; D type 180 ~ 360 m/s ; E type $V_S < 180$ m/s. Almost all the $V_{S\text{-}30}$ values in Table 5 belong to type D soil after this classification (NEHRP RECOMMENDED PROVISIONS, 2000).

CONCLUSIONS

1. The present computed values for seismic velocities are in the same range as others obtained by seismic *in situ* measurements of different types. They are organized in a database (Annex 1) which is a valuable data collection for further studies of the seismic microzonation of Bucharest City.

2. More precise seismic measurements are needed in order to obtain reliable mean velocity values for stratum types 1, 2 and 3, which are responsible for a great part of the amplification factor during an earthquake.

3. Mean weighted values based on *in situ* seismic measurements which will characterize each of the 7 types of sedimentary layers are more likely to be used in the characterization of the elastic properties of the layers over the Bucharest area in hundreds of sites where only geotechnical drillings with lithologic columns are available.

4. The average shear-wave velocity values are computed from the 5 sites investigated by down-hole measurements in Bucharest (Table 3) and presented in

Table 6. Depth of the main geologic layers and average unit weight of the sedimentary layers are also average values from many borehole measurements in the Bucharest area (Ciugudean, 2005; Ciugudean and Stefanescu, 2005).

Table 6

Proposed geotechnical model and average parameters from "in situ" measurements in 5 boreholes from Bucharest area

Geologic layer no.	Depth of the upper limit of the geologic layer [m]	Average unit weight, γ [kN/m^3]	Average Shear-wave velocity V_S [m/s]	Max shear modulus $G_{\max} = V_s^2\gamma / g$ [MPa]
1. Backfill	0	10.8	170	31.82
2. Upper Clay Layer	0.50–5	17.2	234	96.00
3. Colentina Aquifer (sand+gravel)	5–12	19.5	278	153.62
4. Intermediate Clay Layer	10–20	20.3	333	229.58
5. Mostistea Aquifer (fine to medium sand)	15–30	19.6	340	230.96
6. Lacustrine Layer	35–50	21.0	409	358.09
7. Fratesti aquifer A (sand+gravel)	100–180	20.1	543	604.12

5. CONCLUSIONS FOR SPECTRAL RESPONSE OF ACCELERATION IN 4 SPECIFIC SITES OF BUCHAREST AREA

Acceleration response spectra computed at different depth levels by program EDUSHAKE showed the amplification due to the package of sedimentary layers, from 100 m depth to the surface, that are expected to appear in the case of a moderate to strong earthquake motion applied at the bottom of each borehole.

1. The response spectra in acceleration show amplifications of the sedimentary layers at almost the same frequency range, but with different values (1.1x–2x). Lager values of 2–3x can occur locally. These values are obviously dependent on the geologic composition of the sedimentary stack.
2. The period values for the maximum amplification peaks correspond well with the known period domains from the accelerometer recordings in Bucharest, between 0.1–0.6 s for the strong motion applied.
3. Computed Peak ground acceleration (PGA) values at certain levels of depth show that between 30–60 m depth the values are in the same range, but they are growing fast in the range 0–30 m depth. The interval from 0–60 m depth should be characterized completely by "in situ" measurements in much more sites over the Bucharest area.

4. Acceleration response spectra computed by this method prove to be a valuable tool in the evaluation of the seismic microzonation in Bucharest on the basis of the physical and dynamic properties of the sedimentary Quaternary rocks encountered down to 100 m depth.

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ANNEX 1

Table 7

Geologic and geophysical model of the Otopeni borehole

No.	Depth to layer bottom [m]	Thickness [m]	Vp [m/s]	Vs [m/s]	Vs/Vp	Poisson ratio	Natural unit weight $[kN/m^3]$	Lithology
1.	4.5	4.5	500	187	0.374	0.4187	17.5	Soil
2.	9	4.5	1034	187	0.181	0.4831	19.8	Shale
3.	15	6	1034	250	0.242	0.4690	2	Sand
4.	23	8	1034	354	0.342	0.4336	20	Sandy shale
5.	29	6	1333	211	0.158	0.4872	20	Fine sand
6.	32	3	1333	354	0.266	0.4621	20	Fine sand
7.	50	18	1571	354	0.225	0.4733	20.1	Sandy shale
8.	58	8	2250	400	0.178	0.4837	20.1	Sandy shale
9.	62	4	1700	250	0.147	0.4889	20.2	Fine and medium sand
10.	112	50	1700	380	0.224	0.4737	20.1	Shale and sand
11.	118	6	1700	447	0.263	0.4629	20.1	Shale
12.	133	15	2222	447	0.201	0.4789	20.2	Sandy shale
13.	140	7	1555	611	0.393	0.4087	20.5	Marle
14.	148	8	1666	611	0.367	0.4223	20.2	Sandy shale
15.	151	3	1666	310	0.186	0.4821	20.5	Shale
16.	160	9	1666	500	0.300	0.4505	20.5	Shale

(continues)

Table 7 (continued)

No.	Depth to layer bottom [m]	Thickness [m]	Vp [m/s]	Vs [m/s]	Vs/Vp	Poisson ratio	Natural unit weight [kN/m^3]	Lithology
17.	167	7	1666	500	0.300	0.4505	21	Medium sand and gravel
18.	171	4	1666	304	0.182	0.4828	20.5	Shale
19.	200	29	1666	588	0.353	0.4289	22	Shale / sand / gravel

Table 8

Geologic and geophysical model of the Politehnica borehole

No.	Depth to layer-bottom [m]	Thickness [m]	Vp [m/s]	Vs [m/s]	Vs/Vp	Poisson ratio	Natural unit weight [kN/m^3]	Lithology
1.	2.5	2.5	*	*			17.5	Soil
2.	8	5.5	833	227	0.273	0.4599	19.8	Yellow shale with limestone inclusion
3.	10	2	1076	227	0.211	0.4767	20	Medium and coarse sand With gravel
4.	12	2	1076	363	0.337	0.4358	18.2	Yellow shale
5.	14.5	2.5	1076	363	0.337	0.4358	20.5	Medium and fine sand
6.	21.5	7	1413	363	0.257	0.4647	20.5	Yellow shale
7.	25	3.5	944	363	0.385	0.4132	20.5	Medium and fine sand
8.	30.5	5.5	1354	277	0.205	0.4782	20.5	Medium and fine sand
9.	33.5	3	1354	413	0.305	0.4487	20.5	Sandy shale
10.	36.5	3	1818	413	0.227	0.4728	20.5	Sandy shale
11.	43.5	7	1818	300	0.165	0.4860	20.5	Sandy shale
12.	55.5	12	1818	363	0.200	0.4792	20.5	Sandy shale
13.	57.5	2	2835	363	0.128	0.4917	20.5	Sand and shale
14.	60.5	3	2835	363	0.128	0.4917	20.9	Blue compact shale
15.	63.5	3	1117	400	0.358	0.4264	20.5	Fine silty sand
16.	66.5	3	1117	400	0.358	0.4264	21.5	Yellow compact shale
17.	72	5.5	1857	400	0.215	0.4757	22	Fine sand

(continues)

Table 8 (continued)

No.	Depth to layer-bottom [m]	Thickness [m]	Vp [m/s]	Vs [m/s]	Vs/Vp	Poisson ratio	Natural unit weight [kN/m^3]	Lithology
18.	78.5	6.5	1857	400	0.215	0.4757	19.8	Shale with some sand
19.	82.5	4	1055	400	0.379	0.4161	19.8	Shale with some sand
20.	98.5	16	1900	400	0.211	0.4768	19.8	Shale with some sand
21.	99.5	1	1600	400	0.250	0.4667	20	Fine sand
22.	106.5	7	1600	400	0.250	0.4667	21	Blue compact shale
23.	108.5	2	1600	454	0.284	0.4562	20	Sandy shale
24.	112.5	4	1600	454	0.284	0.4562	19.5	Blue shale with some sand
25.	117	4.5	2550	454	0.178	0.4836	19.5	Blue shale with some sand
26.	118.5	1.5	1470	454	0.309	0.4473	20	Fine silty sand
27.	124	5.5	1470	454	0.309	0.4473	21	Blue compact shale
28.	131	7	2800	454	0.162	0.4865	20.5	Blue sandy shale
29.	135	4	2800	454	0.162	0.4865	20.5	Sand and shale
30.	136.5	1.5	2800	454	0.162	0.4865	22.5	Coarse sand and gravel
31.	146	9.5	1315	454	0.345	0.4323	22.5	Coarse sand and gravel
32.	151	5	2222	454	0.204	0.4782	20.5	Blue shale
33.	154	3	2222	612	0.275	0.4590	21	Fine and medium sand
34.	161	7	1600	612	0.383	0.4143	21	Blue compact shale
35.	163	2	1600	508	0.318	0.4439	21	Blue compact shale
36.	165	2	1600	508	0.318	0.4439	20.5	Fine silty sand
37.	167.5	2.5	2400	508	0.212	0.4765	21	Blue compact shale
38.	170	2.5	1746	508	0.291	0.4538	21	Blue compact shale
39.	172	2	1746	508	0.291	0.4538	20.5	Fine silty sand
40.	177.5	5.5	1746	508	0.291	0.4538	21.5	Blue compact shale

(continues)

Table 8 (continued)

No.	Depth to layer-bottom [m]	Thickness [m]	Vp [m/s]	Vs [m/s]	Vs/Vp	Poisson ratio	Natural unit weight [kN/m^3]	Lithology
41.	183	5.5	1746	508	0.291	0.4538	21	Fine and medium sand
42.	186.5	3.5	1746	508	0.291	0.4538	23	Sand and gravel
43.	193	6.5	1746	508	0.291	0.4538	23	Medium sand and gravel
44.	200	7	1746	508	0.291	0.4538	21	Shale and marle

Table 9

Geologic and geophysical model of the borehole IMGB

No.	Depth to layer-bottom [m]	Thickness [m]	Vp [m/s]	Vs [m/s]	Vs/Vp	Poisson ratio	Natural unit weight [kN/m^3]	Lithology
1.	5	5	*	*			17.5	Soil
2.	8	3	*	*			18.5	Yellow weathered shale
3.	11	3	960	370	0.385	0.4128	19.5	Yellow shale with limestone inclusions
4.	20	9	1125	370	0.329	0.4394	20.5	Medium sand and gravel.
5.	22.5	2.5	1666	526	0.316	0.4446	20.5	Medium sand and gravel
6.	30	7.5	1666	526	0.316	0.4446	20	Sandy shale with inclusion of sand
7.	33	3	1666	391	0.235	0.4709	20	Sandy shale with inclusion of sand
8.	0.5	7.5	1050	391	0.372	0.4195	20	Sandy shale with inclusion of sand
9.	43.5	3	2250	391	0.174	0.4844	20	Sandy shale with inclusion of sand
10.	51.5	8	1362	391	0.287	0.4551	20	Sandy shale with inclusion of sand
11.	57.5	6	1571	391	0.249	0.4670	20	Sandy shale with inclusion of sand
12.	60	2.5	1571	227	0.144	0.4893	20	Sandy shale with inclusion of sand
13.	65	5	2321	227	0.098	0.4952	20	Sandy shale with inclusion of sand

(continues)

Table 9 (continued)

No.	Depth to layer-bottom [m]	Thickness [m]	Vp [m/s]	Vs [m/s]	Vs/Vp	Poisson ratio	Natural unit weight [kN/m^3]	Lithology
14.	68	3	2321	377	0.162	0.4865	20	Sandy shale with inclusion of sand
15.	74	6	2321	377	0.162	0.4865	20.5	Blue compact shale
16.	80	6	1190	476	0.400	0.4048	20.5	Blue compact shale
17.	84	4	1190	476	0.400	0.4048	22	Gravel and coarse sand
18.	92	8	2200	256	0.116	0.4931	22	Gravel and coarse sand
19.	97.5	5.5	2200	454	0.206	0.4778	22	Gravel and coarse sand
20.	100	2.5	2200	454	0.206	0.4778	20	Blue plastic shale
21.	107	7	1625	454	0.279	0.4577	20	Blue plastic shale
22.	112	5	2142	454	0.212	0.4765	20	Blue plastic shale
23.	116.5	4.5	1333	454	0.341	0.4344	20	Blue plastic shale
24.	119.5	3	1725	454	0.263	0.4628	20	Blue plastic shale
25.	123	3.5	1725	454	0.263	0.4628	20.5	Fine micaceous sand
26.	130	7	1725	454	0.263	0.4628	22	Medium coarse sand and gravel
27.	134.5	4.5	1725	588	0.341	0.4343	22	Medium coarse sand and gravel
28.	138	3.5	1725	588	0.341	0.4343	21	Blue plastic shale
29.	146.5	8.5	1725	833	0.483	0.3479	21	Blue plastic shale
30.	156.5	10	1725	833	0.483	0.3479	23	Medium coarse sand and gravel

Table 10

Geologic and geophysical model of the borehole Magurele

No.	Depth to layer bottom [m]	Thickness [m]	Vp [m/s]	Vs [m/s]	Vs/Vp	Poisson Ratio	Natural unit weight [kN/m^3]	Lithology
1.	0.5	0.5	*	*	*		*	Soil
2.	3.5	3	*	*	*		16.7	Dusty shale/loess
3.	10.5	7	1492	260	0.174	0.4843	19.5	Coarse sand and gravel

(continues)

Table 10 (continued)

No.	Depth to layer bottom [m]	Thickness [m]	Vp [m/s]	Vs [m/s]	Vs/Vp	Poisson Ratio	Natural unit weight [kN/m^3]	Lithology
4.	13.5	3	1000	345	0.345	0.4324	20	Shale
5.	15	1.5	1000	274	0.274	0.4594	20	Shale
6.	16	1	1000	274	0.274	0.4594	20	Sandy shale
7.	18	2	1000	274	0.274	0.4594	20.1	Fine sand
8.	22	4	1351	274	0.203	0.4786	20.1	Sandy shale
9.	25	3	1000	274	0.274	0.4594	20.1	Sandy shale
10.	29	4	1666	313	0.188	0.4817	20.1	Sandy shale
11.	38	9	1333	313	0.235	0.4708	20.2	Sandy shale with fine sand
12.	54	16	1639	377	0.230	0.4721	20.2	Sandy shale
13.	58	4	2127	425	0.200	0.4792	20.2	Shale
14.	68	10	2127	425	0.200	0.4792	20.2	Shale
15.	73	5	1219	425	0.349	0.4308	20.2	Shale
16.	84	11	1754	425	0.242	0.4688	23	Coarse sand and gravel
17.	94	10	1754	370	0.211	0.4767	21	Blue plastic shale
18.	100	6	1428	370	0.259	0.4640	21	Blue plastic shale
19.	106.5	6.5	1818	512	0.282	0.4569	21	Blue plastic shale
20.	110	3.5	1818	512	0.282	0.4569	22	Fine sand
21.	116	6	1818	512	0.282	0.4569	23	Coarse sand and gravel

Table 11

Geologic and geophysical model of the borehole Policolor_100

No.	Depth to layer bottom [m]	Thickness [m]	Vp [m/s]	Vs [m/s]	Vs/Vp	Poisson Ratio	Natural unit weight [kN/m^3]	Lithology
1.	2.5	2.5	298	153	0.513	0.321	17.5	Soil
2.	10	7.5	950	288	0.303	0.449	19.5	Yellow shale
3.	16	6	950	288	0.303	0.449	20	Sandy shale
4.	19	3	1105	288	0.261	0.463	20	Sandy shale
5.	21	2	1105	288	0.261	0.463	21	Fine micaceous sand
6.	26	5	1105	257	0.233	0.471	21	Fine micaceous sand

(continues)

Table 11 (continued)

No.	Depth to layer bottom [m]	Thickness [m]	Vp [m/s]	Vs [m/s]	Vs/Vp	Poisson Ratio	Natural unit weight [kN/m^3]	Lithology
7.	33	7	1176	305	0.259	0.464	21	Fine micaceous sand
8.	46	13	1750	305	0.174	0.484	19.9	Sandy shale
9.	48	2	1116	305	0.273	0.460	20.5	Fine sand
10.	50	2	1116	305	0.273	0.460	19.9	Sandy shale
11.	67	17	1700	305	0.179	0.483	19.9	Sandy shale
12.	69	2	1700	520	0.306	0.448	21	Fine micaceous sand
13.	78	9	1700	520	0.306	0.448	19.9	Shale
14.	83.5	5.5	1700	410	0.241	0.469	21	Fine micaceous sand
15.	88	4.5	1700	410	0.241	0.469	20	Shale
16.	100	12	2400	410	0.171	0.485	20	Shale

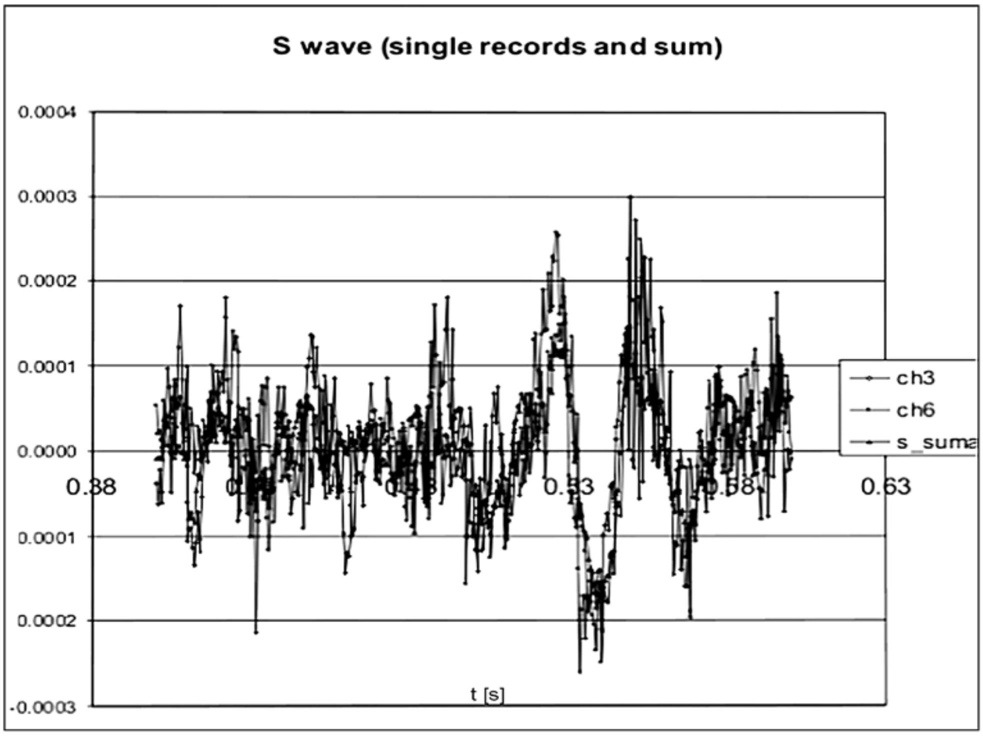

Fig. 9 – Graph of the summation of the S waves, the noise recorded on 2 channels and the summation of the noise.

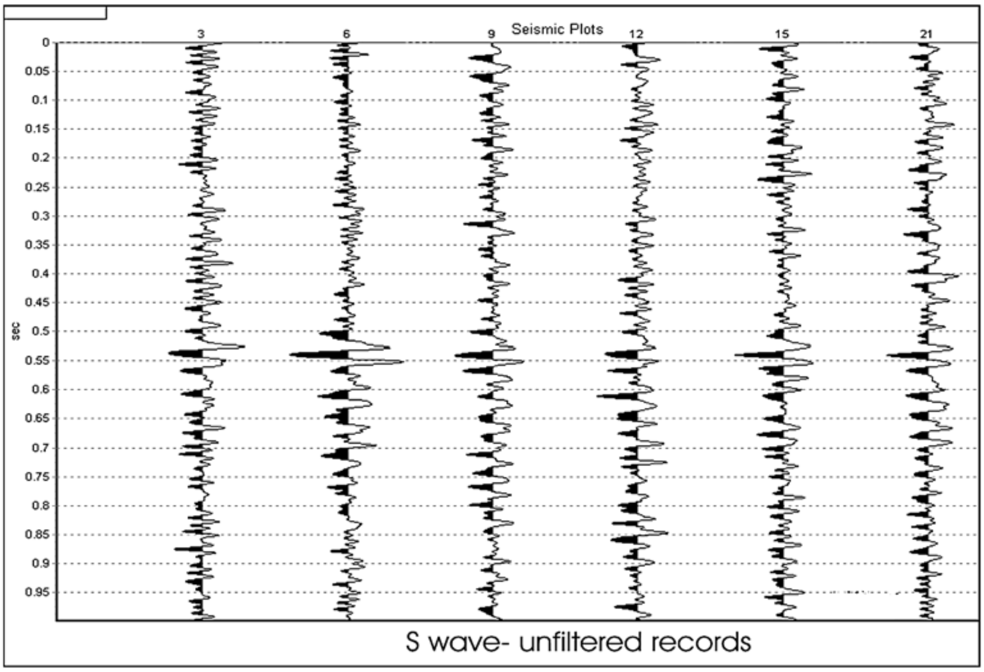

Fig. 10 – Unfiltered recordings – S wave.