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# ESTIMATION OF THE LOCAL RESPONSE USING THE NAKAMURA METHOD FOR THE BUCHAREST AREA*

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*Abstract.* Bucharest is one of the most affected cities by earthquakes in Europe. Situated at 150–170 km distance from the Vrancea epicentral zone, Bucharest has suffered many damages due to high energy Vrancea intermediate-depth earthquakes. For example, the 4 March 1977 event produced the collapse of 32 buildings with 8–12 levels, while more than 150 old buildings with 6–9 levels were seriously damaged. The studies done after this earthquake showed the importance of the surface geological structure upon ground motion parameters. Bonjer *et al.* (1999) used for estimation of the local response the seismic noise recorded at 16 stations in Bucharest. The results showed that the H/V spectral ratios obtained for the 16 sites are dominated by a clear resonance peak between 1 and 2 seconds and their amplitudes remain constant around the value of 2.

Our purpose is to extend the Bonjer *et al.* (1999) study using new data acquired in 2002 on 20 sites in Bucharest. The measurements were done with a K2 digital station equipped with a velocity sensor having the natural period of 5 seconds. For computation of the spectral ratios using Nakamura's method (1989) the JSESAME software developed within the European project SESAME (http://sesame-fp5.obs.ujf-grenoble.fr) was used. The obtained ratios confirm the previous results, showing a dominant resonance in the period range of 1–2 seconds. The average period of these maxima is $1.47 \pm 0.20$ s, while the average amplitude is 2.5. Our results bring evidence of the applicability of the ambient noise measurements and their relevance for the microzonation assessment studies in the Bucharest area.

*Key words:* fundamental period of resonance, seismic microzonation, Nakamura technique, site effects.

## INTRODUCTION

The behavior of the ground motion during an earthquake is generally well explained by the geological surface structure in the place where the phenomenon is studied. Past and recent observations have shown that the damage caused by strong earthquakes are more important in sedimentary basins than on hard rock structures.

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The phenomenon responsible for the amplification of the ground motion in areas with soft sediments is the trapping of seismic waves within sediments due to the acoustic impedance contrast (the product between the mean velocity of the seismic wave in a layer and its mean density) between sediments and bedrock. The interference of these "trapped" waves leads to resonances whose shapes and frequencies are well correlated with the geometrical and mechanical characteristics of the structure.

The city of Bucharest is situated in the Romanian Plane, at 150–170 km distance from the Vrancea epicentral zone, area where earthquakes with high energy (2–3 earthquakes/100 years with $M_w > 7$) occur at intermediate-depths (70–200 km). The geology of the city is characterized by 7 distinct sedimentary complexes (Fig. 1), with different peculiarities and large intervals of thicknesses. These shallow Quaternary complexes were first identified and separated by Liteanu (1951) and then cited by different authors with minor changes (Lungu *et al.*, 1999; Ciugudean and Stefanescu, 2005; Hannich *et al.*, 2005).

Layer 1: **Recent surface sediments**, made up of vegetal soil and clayey sediments, with a thickness locally reaching 15 m.

Layer 2: **Upper sandy-clayey complex**, constituted of loess formations, often moisture sensitive, with sand layers and overall thickness of 16 m in the north and less than 1m on the river side.

Layer 3: **Colentina gravel complex**, made up of gravel and sand (with large variations in the 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.

Layer 4: **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.

Layer 5: **Mostiștea 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.

Layer 6: **Lacustrine complex**, with thickness of 10 m–60 m, 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.

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

Bala *et al.* (2006) determined the dynamic soil parameters by down-hole seismic measurements performed in 10 locations (boreholes) in Bucharest. These measurements represented a combined effort of the National Institute for Earth

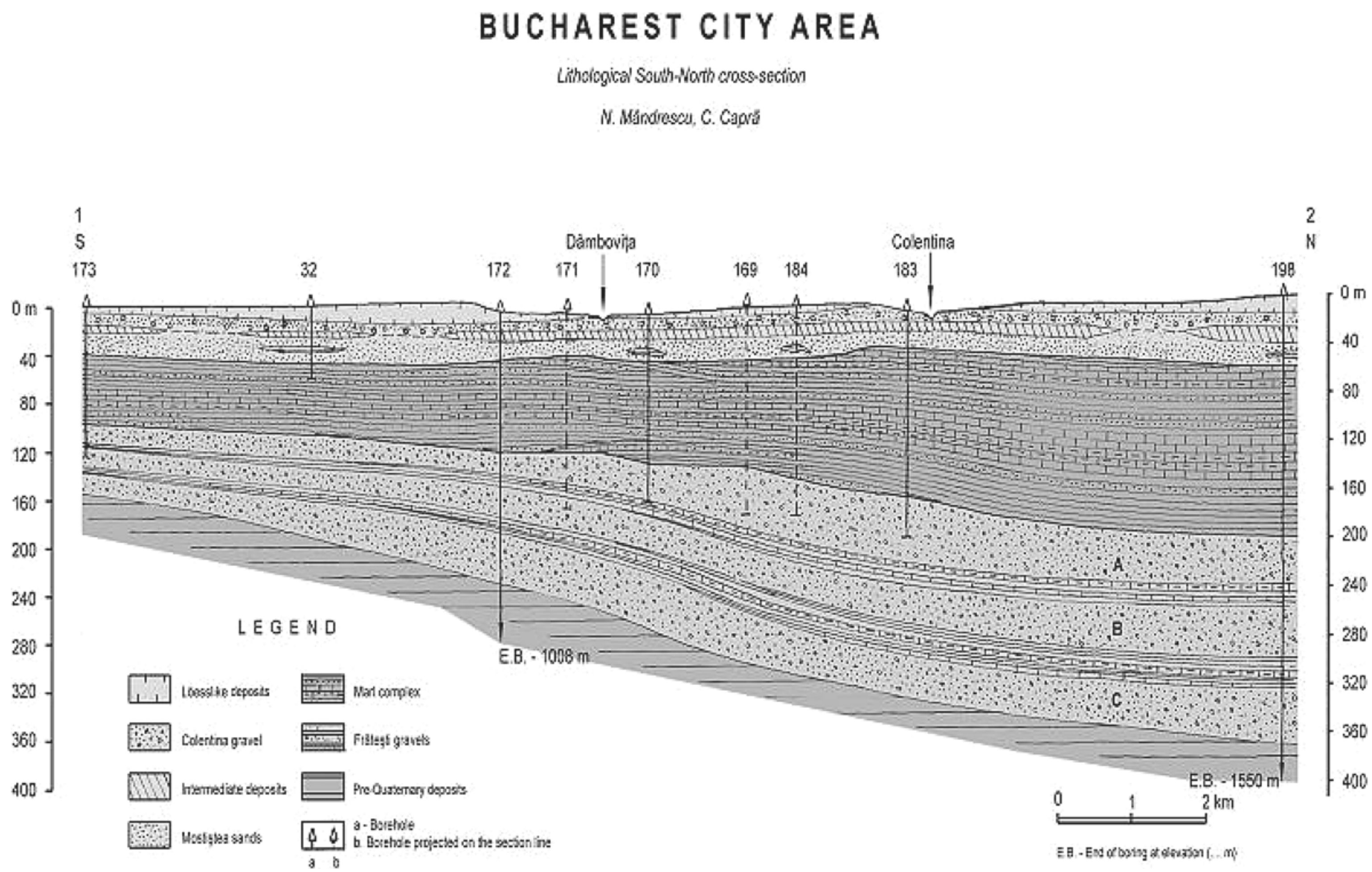



Fig. 1 – Lithological cross-section for Bucharest area (after Mandrescu *et al.*, 2004). One can notice the dipping of the sediments towards north.

Physics (NIEP) and SC “Prospectiuni” S.A. The main properties of the 7 sedimentary complexes are presented in Table 1. The weighted shear-wave velocities written in the table were computed according to the following formula:

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

where $d_i$ and $v_{Si}$ denote the thickness (in meters) and the shear-wave velocity (in m/s) of the ***i-th*** layer, in a total of $n$ layers, existing in the same type of stratum ($d_i$ and $v_{Si}$ were determined by borehole measurements).

*Table 1*

The main properties of the 7 sedimentary complexes

| **Geologic layer** | **Depth of the upper limit of the geologic layer (m)** | **Average density (g/cm$^3$) (Ciugudean and Stefanescu, 2005)** | **Mean weighted shear-wave velocity $V_S$ (m/s) (Bala *et al.*, 2006)** |
|---|---|---|---|
| 1. Backfill | 0 | 1.10 | 170 |
| 2. Upper clay layer | 0.50–5.00 | 1.75 | 234 |
| 3. Colentina aquifer (sand + gravel) | 5.00–12.00 | 1.99 | 278 |
| 4. Intermediate clay layer | 10.00–20.00 | 2.07 | 333 |
| 5. Mostiștea aquifer (fine to medium sand) | 15.00–30.00 | 2.00 | 340 |
| 6. Lacustrine layer | 35.00–50.00 | 2.14 | 409 |
| 7. Frătești aquifer A (sand + gravel) | 100.00–180.00 | 2.05 | 543 |

After the 4 March 1977 event, when 32 buildings with 8–12 levels collapsed and more than 150 old buildings with 6–9 levels were seriously damaged, a serious interest in the estimation of the local response for the area of Bucharest was shown. Among the important studies after the March 1977 event we mention: Sandi and Perlea (1982), who obtained spectral amplification factors nearly constant under 0.15 seconds; Bonjer *et al.* (1999) applied the H/V ratio method for a data set constituted of earthquakes records and ambiental noise records. Mandrescu *et al.* (2004) based on the lithological information compiled from geological, geotechnical and hydrogeological boreholes computed the fundamental periods of the subsurface layers for the entire area of the Bucharest city. He found that the values of the periods vary from 0.9 to 1.9 s, with an increase from the southern to the northern part of the Bucharest. This is in good correlation with the constant increase of the thickness of the Quaternary cohesionless deposits.

One of the most widely used methods for site response estimation using ambient vibration measurements is the so-called Nakamura's technique *(1989).* This technique, initially introduced by Nogoshi and Igarashi (1971), consists in taking the ratio between the Fourier spectra of the horizontal and vertical components of the ambient vibrations. Many studies (Ohmachi *et al.* 1991, Field and Jacob 1993b, Lachet *et al.* 1996, Fah *et al.* 1997) confirmed that these ratios (H/V ratios) are very stable, and on soft soil sites they exhibit a clear peak that is correlated with the fundamental resonant frequency. Regarding the amplitude of the peak, there are still a lot of debates. According to Konno and Ohmachi (1998) there is a good correlation between the amplitude of the H/V peaks and the S-wave site amplification, while other researchers (Lermo and Chavez-Garcia, 1994) suggests that there is no good correlation between the H/V peaks and site transfer function. Lachet and Bard (1994) proposed that the good match at the fundamental frequency is due to horizontal-vertical polarization of the Rayleigh waves, an interpretation that is in agreement with the early Japanese studies (Kudo, 1995).

## DATA USED

To compute the H/V ratios we used in this study a data set which consists of ambiental noise recordings of 15 minutes length. The noise measurements were carried out in June 2002 at 18 sites within the city of Bucharest and two sites at Magurele (Table 2). The noise recordings were recorded with a digital station

*Table 2*

The geographic coordinates of the sites where the noise measurements were done

| **Site** | **Geographic coordinates** | | **Site** | **Geographic coordinates** | |
|---|---|---|---|---|---|
| | Latitude (N) | Longitude (E) | | Latitude (N) | Longitude (E) |
| VIC | 44.45 | 26.08 | BHM | 44.43 | 26.10 |
| UCB | 44.46 | 26.13 | BGM | 44.45 | 26.08 |
| PLV | 44.44 | 26.07 | BFG | 44.43 | 26.10 |
| MTR | 44.36 | 26.20 | BFF | 44.35 | 26.03 |
| IBA | 44.44 | 26.16 | BCU | 44.41 | 26.09 |
| ERE | 44.46 | 26.04 | BAD | 44.24 | 26.03 |
| BVC | 44.43 | 26.10 | B2F | 44.46 | 26.04 |
| BUH | 44.43 | 26.10 | ACD | 44.44 | 26.08 |
| BST | 44.44 | 26.09 | BDL | 44.46 | 26.06 |
| BOT | 44.43 | 26.06 | BTM | 44.43 | 26.10 |
| URS7 | 44.33 | 26.08 | URS23 | 44.36 | 26.12 |

Kinemetrics K2 equipped with a velocity sensor having the natural period of 5 seconds. We also used, for interpolation reasons (Fig. 3), two stations from the temporary network deployed for 6 months in Bucharest within the Urban Seismology project (URS – Ritter *et al., 2005*).

The data were processed using the JSESAME software developed within the European project SESAME (http://sesame-fp5.obs.ujf-grenoble.fr). To determine the H/V ratios the following procedure was applied:

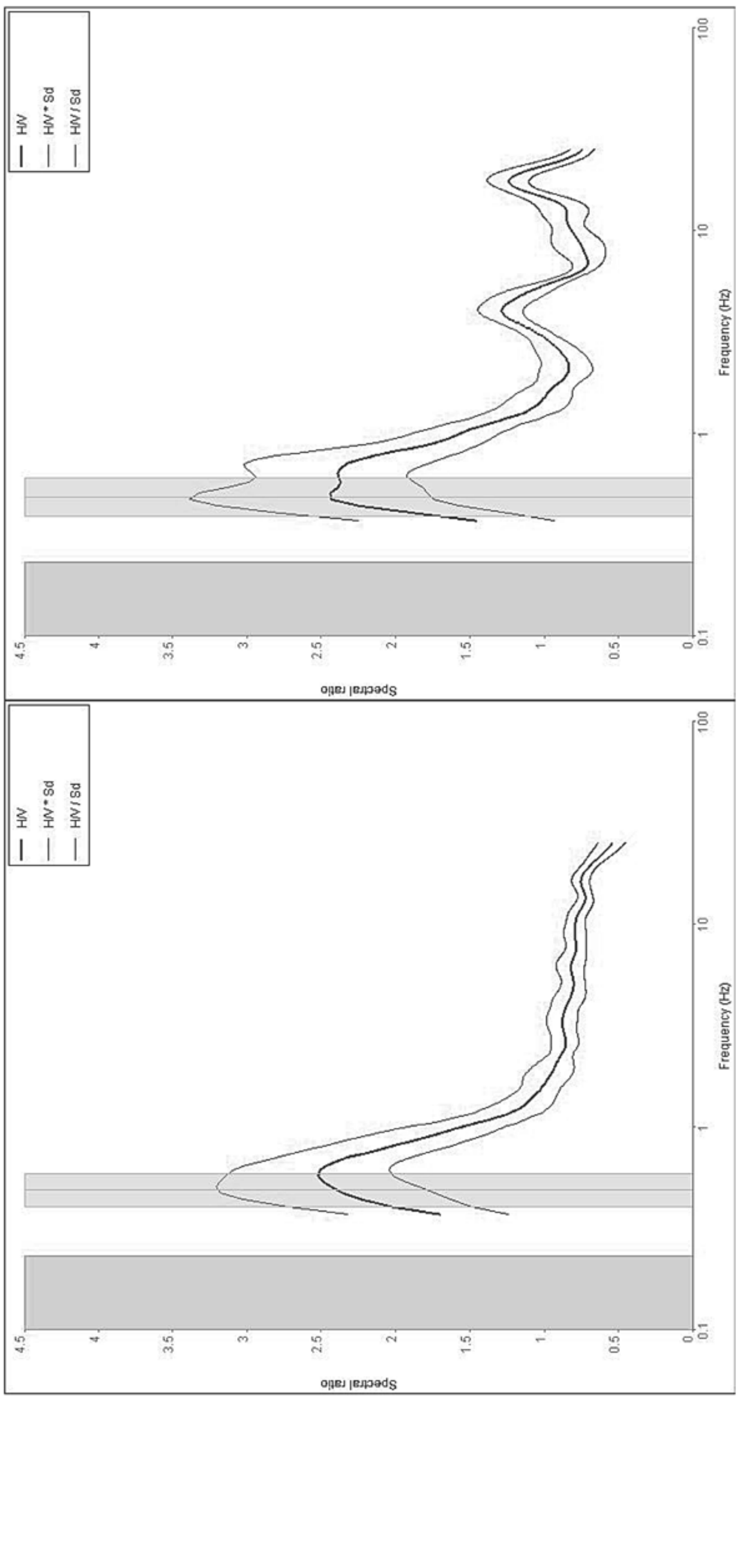
- data were converted from Kinemetrics format to SESAME ASCII format;
- windows of 30 seconds length were automatically selected using an anti-STA/LTA trigger algorithm;
- cosines type window tapering on 5% of the signal were applied;
- Fourier spectra of the three components (NS, EW, Z) were calculated;
- calculated Fourier spectra of the three components were smoothed with Konno-Ohmachi window having the bandwidth of 20;
- the horizontal components were merged by geometric mean (sqrt(specEW* *specNS));
- the H/V spectral ratios were calculated by dividing the spectra of the merged horizontal components to the spectra of the vertical component.

## RESULTS

Following the procedure described above, we computed in the end 22 H/V ratios. If we look at the results (Fig. 2, Table 3), we can see that all the H/V ratios, with no exception, exhibit a dominant peak of which period varies between 1 and 2 seconds. The average period of the maxima of these peaks is T = 1.47 ± 0.20 seconds. The amplitude of these peaks varies slowly from 2.05 at BVC site to 2.95 at BDL site (Fig. 3, Table 3), while only two sites (BAD and BFF) exhibit peaks with amplitude smaller than 2. The remarkable similarity of the amplitudes and the shapes of the peaks suggest that there are no significant lateral variations and impedance contrasts within the subsoil of Bucharest. No further resonance peaks with amplitudes greater than 1.5 are visible at periods greater than 0.1 s, except for the site URS23 where a secondary peak can be identified at around 9 Hz. The distribution of the fundamental periods of resonance determined by the H/V ratios (Fig. 3) indicates an increase of the period from south to north, which correlates rather well with the increase of the sediments towards the northern part of the city of Bucharest.

To check our results, we used the values from Table 1 and we computed the fundamental period by applying the following formula:

$$T = \frac{4 \cdot h}{\beta} \qquad (2)$$




ACD site

BCU site

Fig. 2a – Examples of H/V ratios.

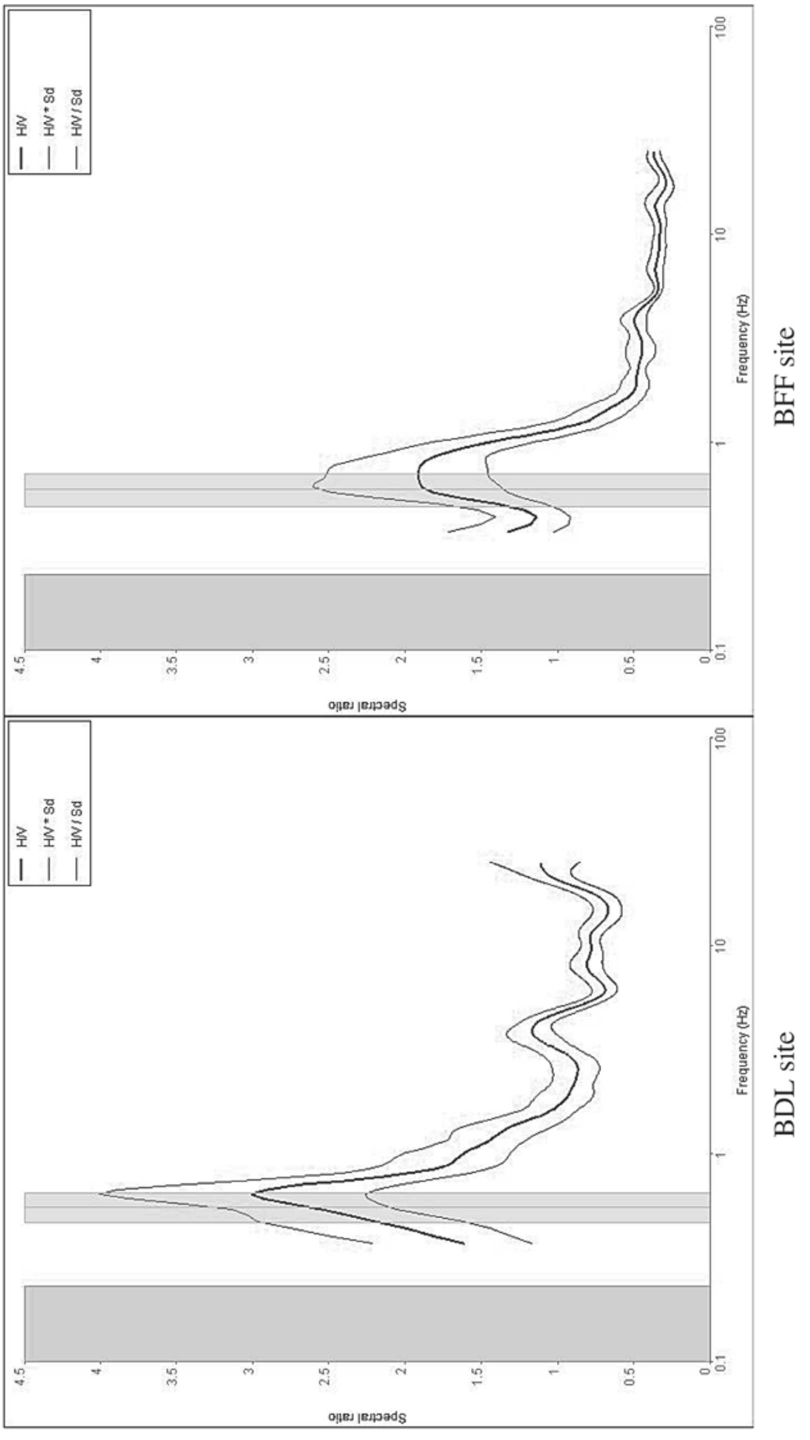



Fig. 2b – Examples of H/V ratios.

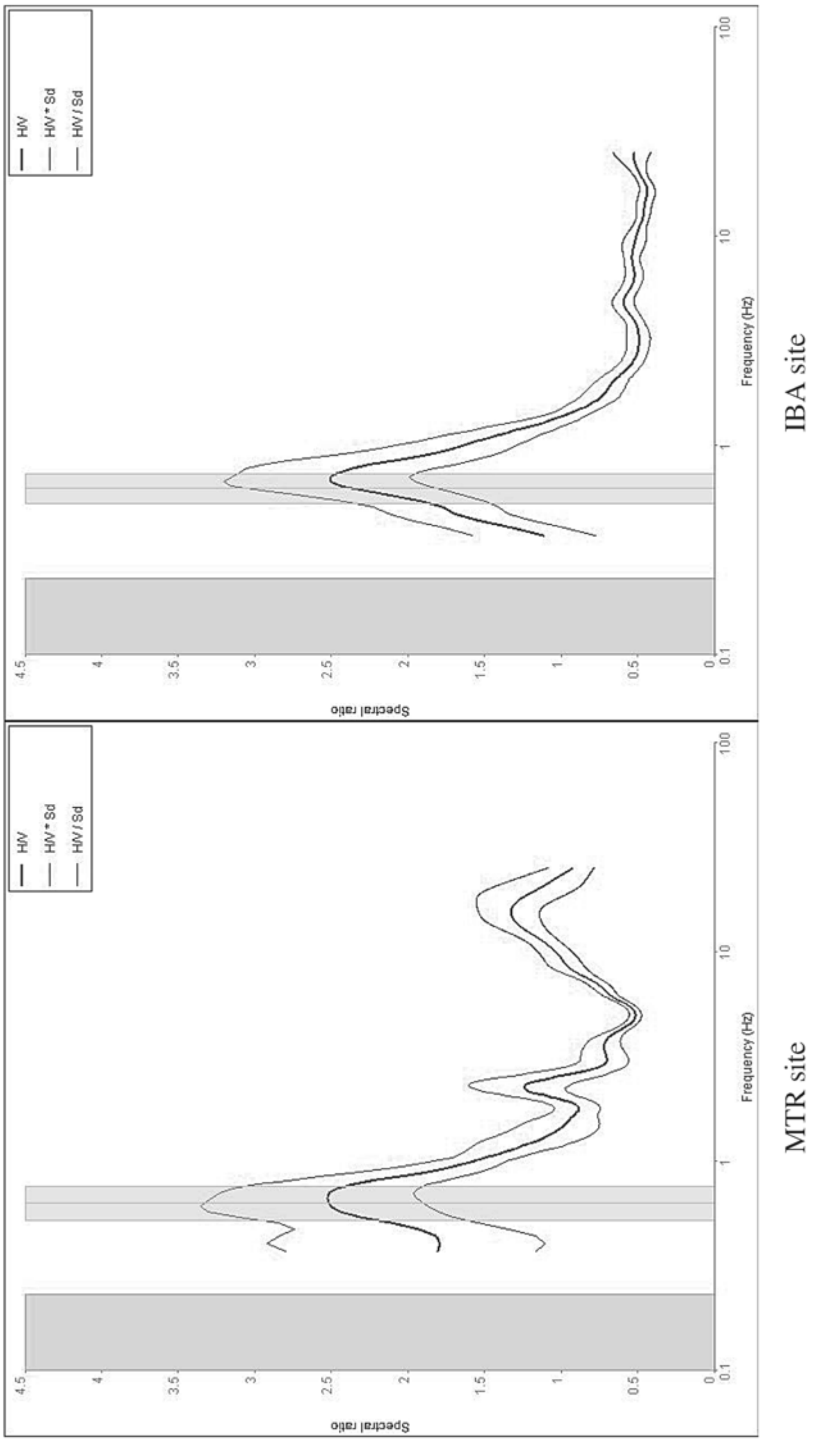
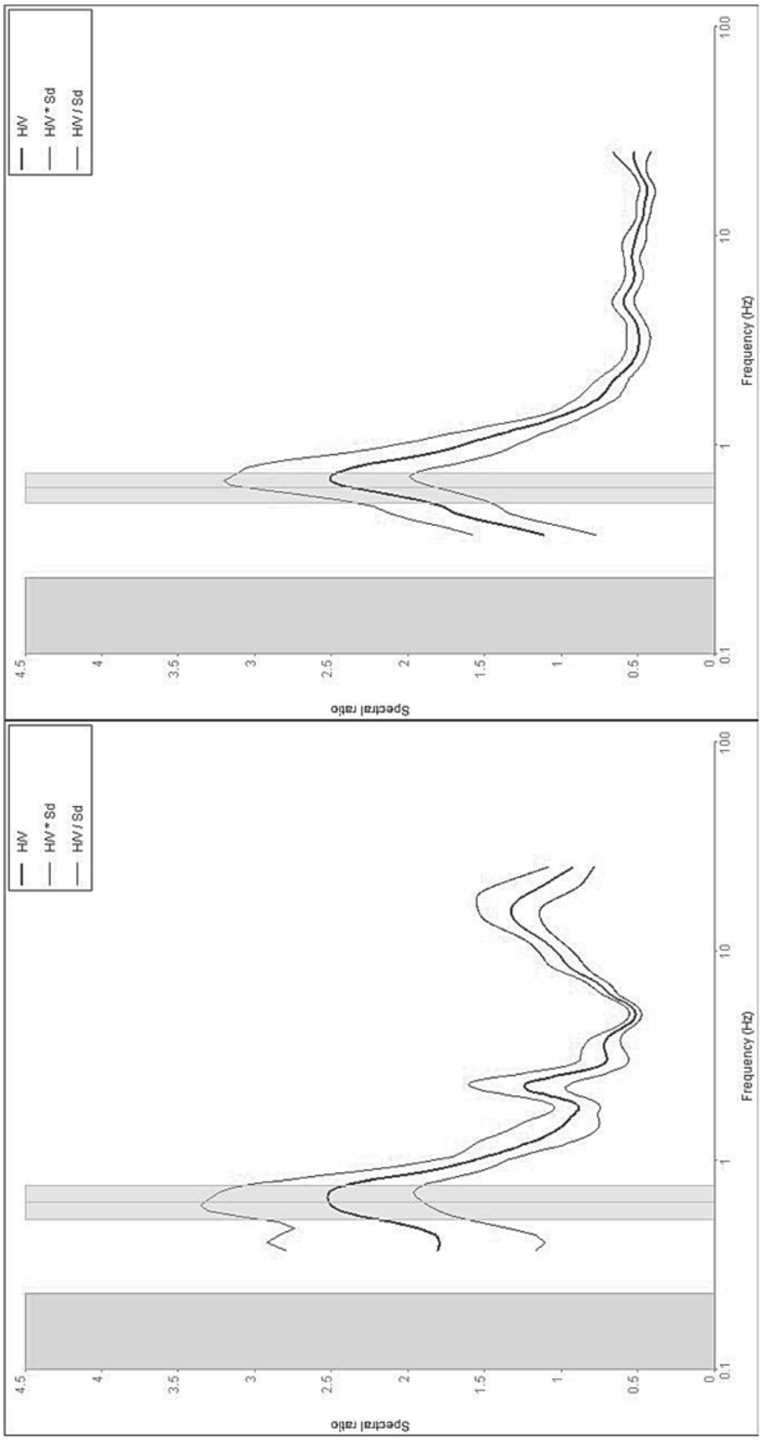



Fig. 2c – Examples of H/V ratios.




MTR site

IBA site

Fig. 2d – Examples of H/V ratios.

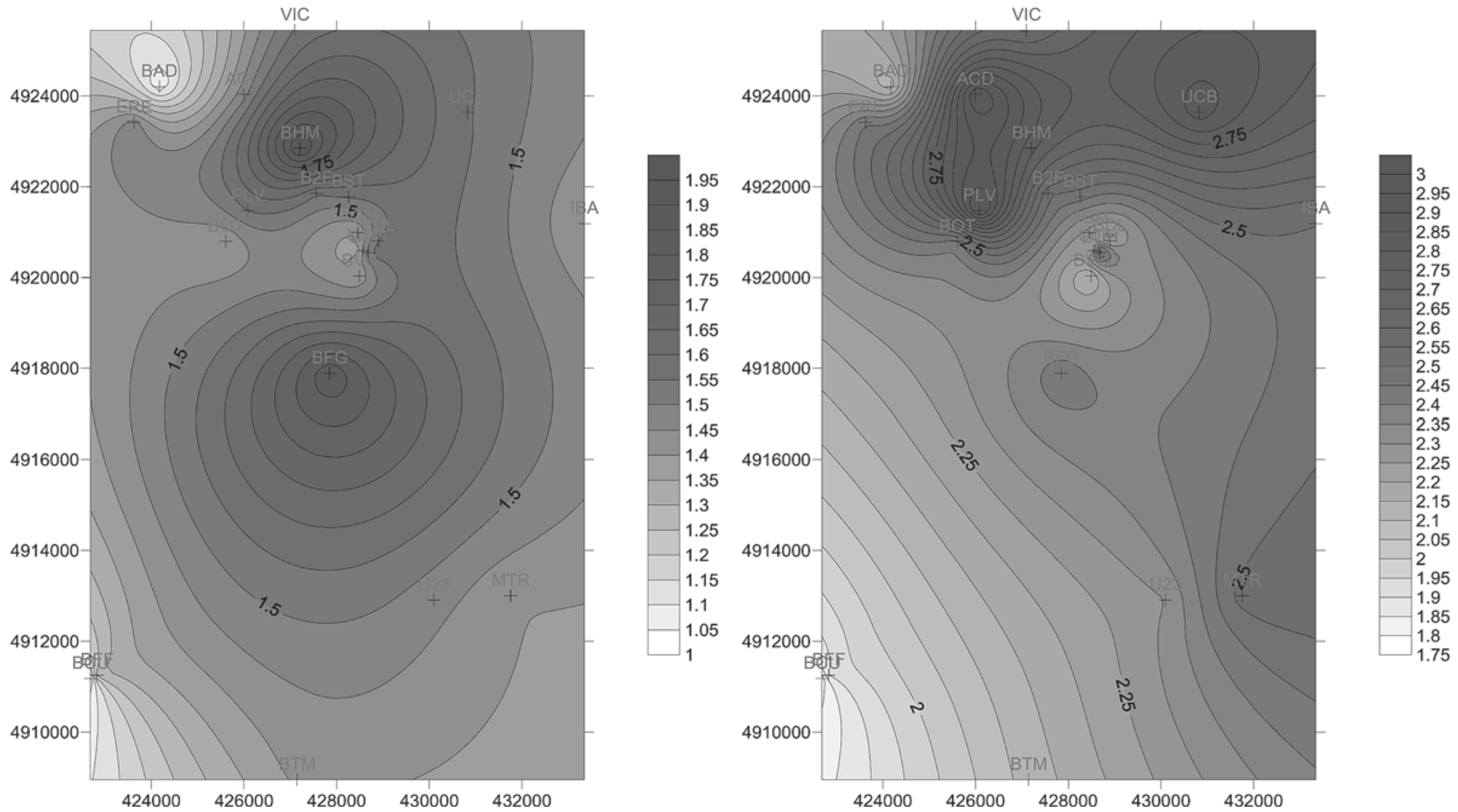



Fig. 3 – Distribution of the fundamental period of resonance (left) and of the amplitude of the H/V dominant peaks (right).

where *h* is the thickness (in m) of the sediments overlying the half-space and β is the shear-wave velocity (in m/s) in the sediments. In our computations we considered one layer (made of the first 6 sedimentary complexes described above) which overlies the half-space (the Frăţeşti layer). The shear-wave velocity in the sedimentary layer was calculated using formula 1, while for the depth we considered 3 cases: the minimum depth $h_{min}$ = 100 m when we chose for each of the 6 complexes the minimum depth, the average depth $h_{avg}$ = 140 m when we chose an average depth for each complex, and the maximum depth $h_{max}$ = 180 m when we chose the maximum depth for each complex (see depth values in Table 1). We obtained the following fundamental periods: $T_1$ = 1.09 s (for $h_{min}$), $T_2$ = 1.53 s (for $h_{avg}$) and $T_3$ = 1.97 s (for $h_{max}$). It can be noticed that the average period obtained from H/V ratios and $T_2$ are very close.

Two of the boreholes presented in Bala *et al.*, 2006 (IMGB and NIEP) were drilled close to two sites were noise measurements were done (MTR and BFF). Applying the same procedure as above we found for IMGB a fundamental period of 1.35 s and for NIEP 1.23 s. From H/V ratios we obtained at MTR (IMGB) 1.41 s and at BFF (NIEP) 1.29 s.

*Table 3*

Resonance periods and their amplitudes obtained from H/V ratios

| **Site** | **Resonance period (s)** | **Frequency (Hz)** | **Amplitude** | **Site** | **Resonance period (s)** | **Frequency (Hz)** | **Amplitude** |
|---|---|---|---|---|---|---|---|
| VIC | 1.56 | 0.64 | 2.59 | BHM | 1.41 | 0.71 | 2.34 |
| UCB | 1.56 | 0.64 | 2.88 | BGM | 1.97 | 0.51 | 2.52 |
| PLV | 1.56 | 0.64 | 2.72 | BFG | 1.41 | 0.71 | 2.50 |
| MTR | 1.41 | 0.71 | 2.47 | BFF | 1.29 | 0.78 | 1.85 |
| IBA | 1.41 | 0.71 | 2.49 | BCU | 1.85 | 0.54 | 2.31 |
| ERE | 1.48 | 0.67 | 2.40 | BAD | 0.99 | 1.02 | 1.52 |
| BVC | 1.41 | 0.71 | 2.05 | B2F | 1.06 | 0.95 | 2.20 |
| BUH | 1.56 | 0.64 | 2.64 | ACD | 1.56 | 0.64 | 2.40 |
| BST | 1.56 | 0.64 | 2.33 | BDL | 1.48 | 0.68 | 2.95 |
| BOT | 1.41 | 0.71 | 2.27 | BTM | 1.56 | 0.64 | 2.12 |
| U07 | 1.41 | 0.71 | 2.12 | U23 | 1.48 | 0.68 | 2.30 |

## CONCLUSIONS

The H/V ambient vibration method (Nakamura’s technique) has become in the last two decades one of the most popular methods for estimating site response in urban areas. For the city of Bucharest, Bonjer *et al.* (1999) applied this technique for 16 sites. They found a remarkable similarity of the H/V curves between 0.1 to 10 seconds. The period of the identified resonance peaks varies in a narrow band from 1.2 to 1.6 seconds with an average value of T = 1.36 ± 0.14.

Our study is an extension continuation of the above mentioned study. We computed the H/V ratios for 20 sites in Bucharest area and the results also show a clear peak in all ratios whose period varies from 0.99 to 1.85 seconds. The average period of these peaks is T= 1.47 ± 0.20 seconds. This period correlates well with the fundamental period ($T_2$) computed when we consider one layer overlying the half-space (Fratesti complex).

The fundamental periods obtained with Nakamura's method are in good agreement with those computed on the basis of geological and geotechnical data which show an increase of the fundamental period in the Bucharest area from south to north, in the same direction as the increase of the thickness of the cohesionless Quaternary deposits.

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## REFERENCES

1. A. Bala, V. Raileanu, I. Zihan, V. Cigudean, B. Grecu, *Physical and dynamic properties of the shallow sedimentary rocks in the Bucharest metropolitan area*, Rom. Rep. Phys., Vol. 58, No. 2, 2006, p. 221–250.
2. K.-P. Bonjer, M. C. Oncescu, L. Driad, M. Rizescu, *A note on empirical site responses in Bucharest*, Romania, 1999.
3. F. Wenzel *et al.* (eds.), *Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation*, Kluwer Academic Publishers, 1999, 149–162.
4. V. Ciugudean, I. Stefanescu, *Engineering geology of the Bucharest city area*, Romania, submitted to IAEG – 2006, 2005 paper no. 235.
5. D. Fah, E. Ruttener, Th. Noack and P. Kruspan, *Microzonation of the city of Basel*, Journal of Seismology, 1, 1997, p. 87–102.
6. E. H. Field, K. Jacob, *The teoretical response of sedimentary layers to ambient seismic noise*, Geophysical res. Lett. 20–24, 1993, p. 2925– 2928.
7. D. Hannich, K.-P. Bonjer, H. Hoetzl, D. Lungu, V. Ciugudean, T. Moldoveanu, C. Dinu, D. Orlowsky, *Evaluation of soil parameters through Vertical Seismic Profiling (VSP) in Bucharest, Romania,* paper submitted to SOIL DYNAMICS AND EARTHQUAKE ENGINEERING, Elsevier Science Ltd, Oxford, 2005.
8. K. Konno, T. Ohmachi, *Ground motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremor*, Bull. Seism. Soc. Am. 88–1, 1998, p. 228–241.

9. K. Kudo, *Practical estimates of site response, State-of-the-Art report*, in: Proceedings of the Fifth International Conference of Seismic Zonation, October 17–19, Nice, France, Ouest Editions Nantes, 3, 1995, p. 1878 – 1907.
10. C. Lachet, P.-Y. Bard, *Numerical and theoretical investigations on the possibilities and limitations of the „Nakamura's'' techniques*, J. Phys. Earth. 42, 1994, p. 377–397.
11. J. Lermo, F. J. Chavez-Garcia, *Site effect evaluation using spectral ratios with only one station*, Bull. Seism. Soc. Am. 83, 1993, p. 1574–1594.
12. G. Liteanu, *Geology of the city of Bucharest. Technical Studies*, Series E, Hydrogeology, Bucuresti, No. 1, 1951 (in Romanian).
13. D. Lungu, A. Aldea, T. Moldoveanu, V. Ciugudean, M. Stefanica, *Near Surface Geology and dynamic properties of soil layers in Bucharest, in Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation*, Contributions from the First International Workshop on Vrancea Earthquakes, Bucharest, Romania, 1–4 November 1997. Editors F. Wenzel, D. Lungu, O. Novak, Kluwer Academic Publishers, 1999, p. 137–148.
14. N. Mândrescu, M. Radulian, G. Mărmureanu, *Site conditions and predominant period of seismic motion in the Bucharest urban area*, Rev. Roum. Geophysique 48, 2004, p. 37–48.
15. Y. Nakamura, *A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface*, Q.R. of R.T.R.I., 30–1, 1989, p. 25–33.
16. M. Nogoshi, T. Igarashi, *On the amplitude characteristics of microtremor* (Part 2), Jour. Seism. Soc. Japan, 24, 1971, p. 26–40 (in Japanese with English abstract).
17. T. Ohmachi, Y. Nakamura, T. Toshinawa, *Ground motion characteristics in the San Francisco Bay area detected by microtremor measurments*, in: Proceedings of the Second International Conference on Recent Advances in Geotechnical Earthquake Engeneering and Soil Dynamics, March 11–15, St. Louis, Missouri, S. Prakash (editor), Univ. of Missouri-rolla, 1991, p. 1643–1648.
18. J. R. R. Ritter, S. F. Balan, K.-P. Bonjer, T. Diehl, T. Forbinger, G. Marmureanu, F. Wenzel, W. Wirth W., 2005, *Broadband urban seismology in the Bucharest metropolitan area*, Seismological Research Letters, 76, no. 5.
19. H. Sandi, V. Perlea, *Engineering studies on ground motion, seismological reserches on 4 of March 1977 earthquake*, Cornea, I. and Radu (Editors). CSEN – Center for Earth Physics and Seismology, Bucharest, 773 p., 1982.