PRACTICAL INSIGHTS ON SEISMIC RISK EVALUATION FROM SITE-STRUCTURE DYNAMIC BEHAVIOR PERSPECTIVE FOR BUCHAREST URBAN AREA

C. O. CIOFLAN, M. RADULIAN, C. IONESCU, S. F. BALAN, B. F. APOSTOL

National Institute for Earth Physics, Călugăreni Street, 12 Măgurele, Romania,
Corresponding author e-mail: apostol@infp.ro

Received December 4, 2017

Abstract. The paper goal is to discuss some aspects regarding the influence of the dominant periods of the soil layers and fundamental periods of the built structure, starting from earthquakes records and using already known data about the oscillation period of the subsoil. We will focus our analysis on Bucharest Metropolis foundation soils, where buildings are placed in an area exposed to high seismic hazard. The regions of the south-east and south of Romania are affected mainly by the Vrancea strong earthquakes, generated at the South-Eastern Carpathians Arc bend at intermediate depth. In the XXth century four major earthquakes ($M_w > 7$) were reported. The methods used for computing the oscillation period of the soil are reviewed. By knowing the dominant periods over the Bucharest area, we can appreciate if a building is suitable or not for a specific site. In the authors' opinion, it is safer to pick the right structure to be build up in a given area than to force a non-resonance design in that place. Consequently, some seismic risk considerations from soil-foundation-structure interaction perspective will be presented. This will have to be a very effective way of getting the right answers when trying to build a special construction on a site.

Key words: site evaluation, structure natural period, dynamic behavior, seismic action.

1. INTRODUCTION

Bucharest, the capital of Romania, with more than 2 million inhabitants, is considered after Istanbul the second-most earthquake-endangered metropolis in Europe. It is identified as a natural disaster hotspot by a recent global study of the World Bank and the Columbia University [1]. Four major earthquakes with moment magnitudes (M_W) between 6.9 and 7.7 hit Bucharest in the last 68 years. The most recent destructive earthquake of 4th March 1977, with a moment magnitude of 7.4, caused about 1.500 casualties in the capital alone. All disastrous earthquakes are generated within a small epicentral area – the Vrancea region – about 150 km North-East of Bucharest. Thick unconsolidated sedimentary layers in the area of Bucharest amplify the arriving seismic shear-waves causing severe destruction and enhancing the seismic hazard through alteration of the ground motion response, due to what is known as site effects. Sediments tend to amplify

the ground motion but, on the other hand, the earthquake induces material deformation (soil nonlinearity) which can cause liquefaction and instabilities. An example is the case of the 1985 Mexico City earthquake (Mw = 8.0) where the ground motion recorded on the sediment area was almost 5 times larger than the one recorded on bedrock area. The amplification of ground motion is caused by the impedance between bedrock and sediments. The 1989 Loma Prieta earthquake, with effects on soft soil in Bay Area, is also important because of adding empirical data [2]. The importance of site effects and therefore their importance in risk studies have been observed as well throughout several other earthquakes, such as the 1994 Northridge earthquake, the 1995 Kobe earthquake, with ground motion recorded in sediments modified compared to the one in bedrock.

Thus, disaster prevention and mitigation of earthquake effects is an issue of highest priority for Bucharest and its population (see Fig. 1).

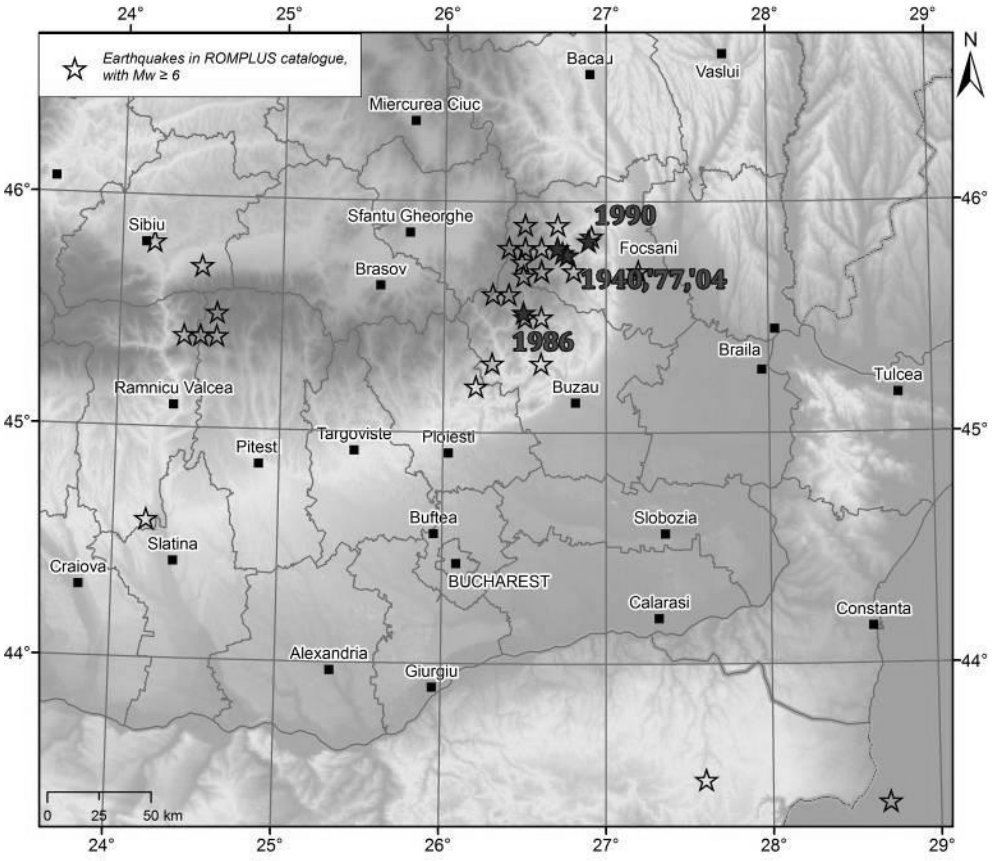

Fig. 1 – Major earthquakes ($M_W \geq 6$) described in the ROMPLUS Catalogue, and the location of Bucharest.

The risk studies are recently presented as an innovative approach through its combined analysis of the available records and macroseismic information completed with numerical simulations since the strong motion records are rather scarce. New features regarding site effects evaluation and its role in seismic hazard analysis at regional and/or local scale must be included also in seismic risk analysis. These include also the nonlinear aspects of seismic ground motion induced by strong Vrancea intermediate events and their implication on soil behavior and building design.

We will focus first on the analysis of Bucharest Metropolis foundation soils, where buildings are placed in an exposed area to high seismic hazard. The regions of the south-east and south of Romania are affected mainly by Romania Vrancea strong earthquakes. Only in the XX-th century there have been several major earthquakes, November 10, 1940, Mw ~ 7.5, March 4, 1977, Mw = 7.4, August 30, 1986, Mw = 7.1 and May 30, 1990, Mw = 6.9; in the seismic event of 1940 some several hundred victims, in 1977, about 1500 people died and major building damage on both earthquakes, most of it in Bucharest alone.

2. EVIDENCE OF LOCAL EFFECTS FROM GEOTECHNICAL MEASUREMENTS

Within NATO SfP Project 981882, collaboration between National Institute for Earth Physics (NIEP) and Geophysical Institute of the Karlsruhe University, 10 new, 50 m deep, boreholes were drilled to recover cores for geotechnical laboratory tests and to measure *in situ* seismic velocities. Therefore, a unique, homogeneous dataset of soil-mechanic and elasto-dynamic parameters of the subsurface soils of Bucharest was achieved during this project. These parameters are the input information to model seismic sites response. In a second step, the results of the modeling were compared with the observed site responses (recorded seismograms) to derive the relationship between the measured subsurface soil / rock properties and the observed seismic amplitudes. Then this calibrated relationship can be applied to other available boreholes lithology in the metropolitan area of Bucharest in order to develop an optimized seismic microzonation of the metropolitan area of Bucharest which will be implemented for the future urban planning. In this section we report about the geotechnical measurements that later could be used for linear and non-linear wave propagation simulations.

A number of 250 soil and rock samples were gathered from the 10 drill sites (Figure 2) by the Department of Engineering Seismology of NIEP. These samples were carefully selected without disturbances (sampling as it was recovered from the tube of the drilling machine) and partly disturbed (soil samples which had no

proper consistency). Samples were processed with the help of resonant columns and dynamic triaxial.

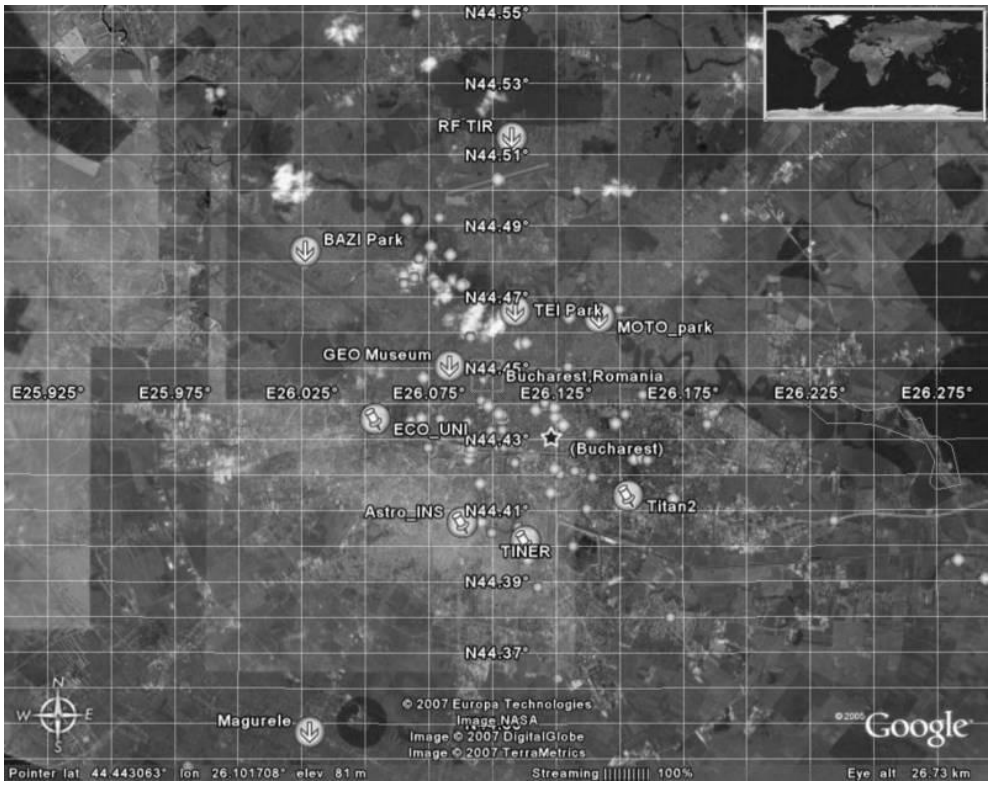

Fig. 2 – Map of the Bucharest City area with location of the investigated boreholes.

Geotechnical parameters and dynamic functions for types of materials from the superficial layers obtained from these laboratory tests were used for local structure modeling. Using the approach proposed by Cioflan *et al.* 2009 [3], the local seismic response at several investigates sites has been computed. We present an example for seismic station INC, simulated for the strongest events recorded at this site, having Mw = 7.4 (March 4, 1977) and 7.1 (August 30, 1986), together with three real earthquakes with magnitudes from 6 to 6.9, and one hypothetic event, "the maximum possible earthquake", with magnitude Mw = 7.7. The local effects described in terms of amplification spectra are represented in Figure 3. It can be observed that seismic excitation produces strong amplifications in the local structure, especially for "small" magnitude earthquakes: Mw = 6.0 (October 27, 2004), respectively Mw = 6.4 (May 31, 1990 – denoted 1990-2); for strong earthquakes (denoted 1977, 1986, maximum), the transfer functions representing the ground motion amplifications decrease as earthquakes magnitude increase.

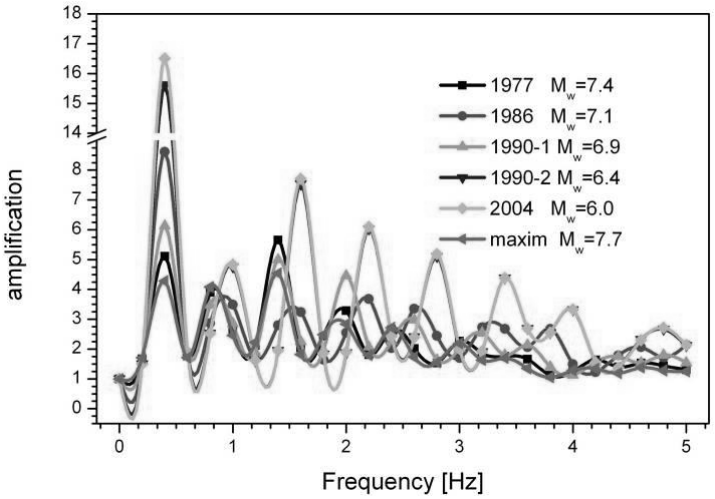

Fig. 3 – The transfer functions for site INC (Cioflan *et al.*, 2009 [3]).

3. DISTRIBUTION OF FUNDAMENTAL PERIOD IN BUCHAREST AREA

Bucharest needed an updated map of soil fundamental period distribution. One solution to obtain it is to use recorded signals at all available stations. Oscillation periods of the ground depend on the magnitude of the earthquake and we are interested in dominant periods corresponding to strong earthquakes. In the last century only two strong earthquakes (1986 and 1990) were recorded in Bucharest area, not making available enough data to build a reliable map based on seismic records.

For these reasons we had to apply other methods that consider the geological and geophysical characteristics of the city underground. The geological structure of the city is known, consisting of transverse layers, with their wave velocity. The soil fundamental period, T_g, usually was calculated employing a simple approximate relationship of the form:

$$T_g = 4H / Vs \tag{1}$$

where H is the thickness above the bedrock deposits and V_S is transverse wave propagation velocity. Bedrock can be considered any rock hard enough (compact), whose properties do not change during local shocks induced by earthquakes. Typically, Neogene or Pleistocene formations, well strengthened, with certain constraints in terms of geological and geophysical properties, could be considered as bedrock. Mândrescu *et al.* [4] considers, for Bucharest, as bedrock layers of Fratesti compact horizon, for which was considered average speed of transverse

seismic wave 650 m/s. As the city basement is composed of several layers, the average speed is determined, using the relationship:

$$(V_S)_{\text{average}} = \sum_{i=1}^{n} h_i \,/\, \sum_{i=1}^{n} h_i \,/\, V_{Si} \tag{2}$$

where h_i is thickness and V_{Si} transverse waves velocity in i layer. Fundamental period was calculated in 120 deep geological drilling locations, distributed somewhat evenly across its surface area. In the calculation, in eq. (1), was used the average velocity of the transverse waves from eq. (2) and the total thickness of the layers above the horizon Fratesti for H value. Map representing the distribution of predominant period (Fig. 4) resulting from interpolation of the computed values is presented below.

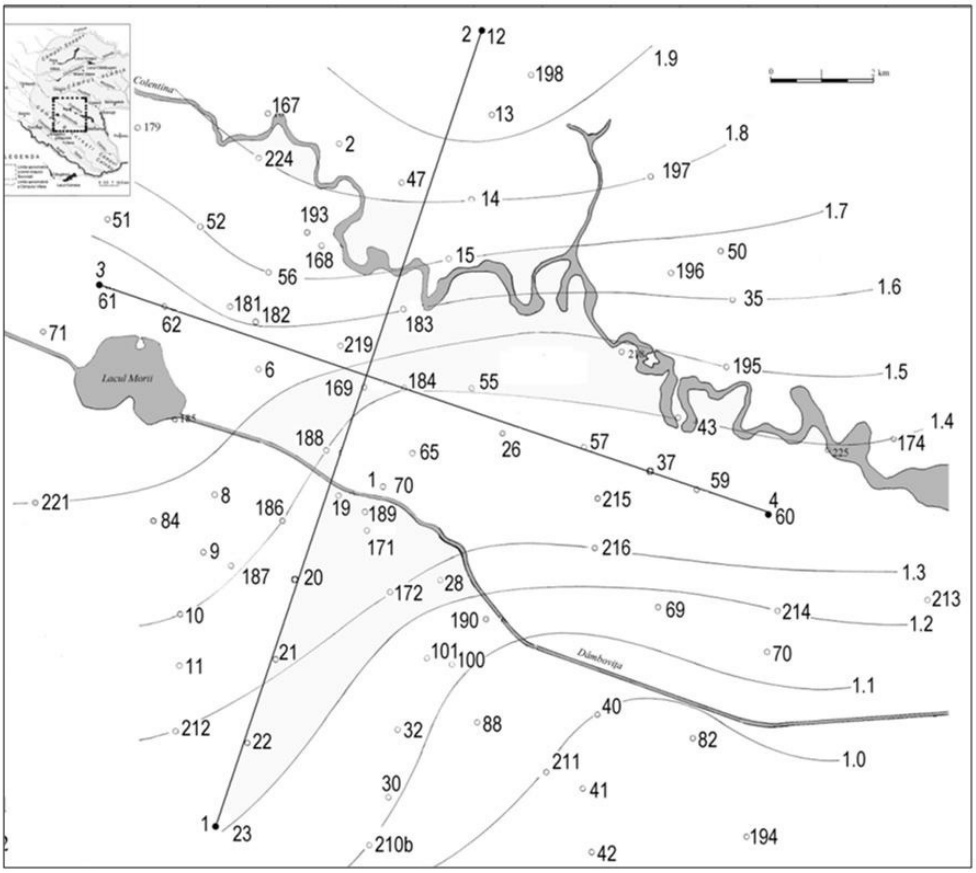

Fig. 4 – Distribution of predominant periods over Bucharest. 1–2 cross sections; boreholes numbers and contour lines for periods [4].

4. SOIL DEPOSITS PREDOMINANT PERIODS

4.1. DURING ROMANIAN STRONG EARTHQUAKES IN THE XX-TH CENTURY

The March 4, 1977 earthquake was recorded at a single station in Bucharest (station INCERC) and that is why we chose this station to compare the recordings of earthquakes of 1986 and 1990 on the same site. Figure 5 shows the acceleration response spectra for earthquakes of March 4, 1977 (M_W = 7.4; T = 1.54 seconds), August 30, 1986 (M_W = 7.1; T = 0.6 seconds) and 30 May, 1990 (M_W = 6.9; T = 0.47 seconds), recorded at station INCERC Bucharest, NS components, the fraction of critical damping ζ = 5% [5].

We also present in the Figure 6 response spectra of other smaller earthquakes at the same station to have the same term of comparison.

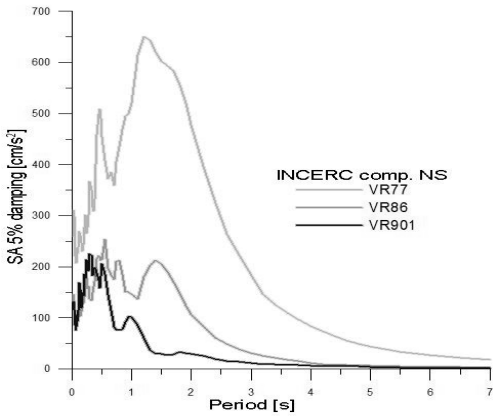

Fig. 5 – Response spectra for 1977, 1986 and 1990 earthquakes.

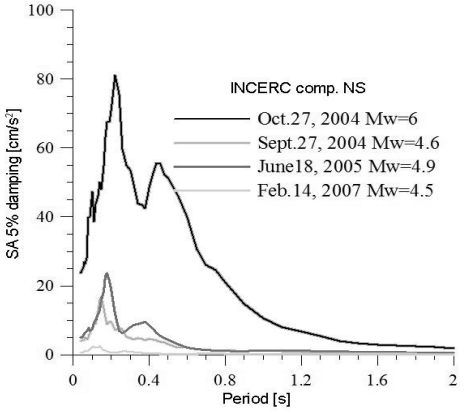

Fig. 6 – Response spectra for 2004, 2005, 2007 Earthquakes.

Thus we have the acceleration response spectra for smaller earthquakes October 27, 2004 (M_W = 6.0; T = 0.22 seconds), September 27, 2004 (M_W = 4.6; T = 0.15 seconds); June 18, 2005 (M_W = 4.9; T = 0.18 seconds) and February 14, 2007 (M_W = 4.5; T = 0.14 seconds), the fraction of critical damping, ζ = 5% (Fig. 6) [5]. From these figures, it can be seen the general tendency, even quite slightly, of increasing for soil predominant periods as the magnitude increases, for a certain site (INCERC). It seems like the higher magnitude, the thicker strata package engaged in oscillation motion, with its specific oscillating frequency. If we are choosing two sites (NIEP and INCERC), for two different rather strong magnitudes, the peak ground accelerations values are bigger for Magurele-NIEP site – station BMG (see Figures 7 and 8). Therefore, this should be a matter

of local site conditions. In the same time the peak ground acceleration for the 1990 earthquake (small one, M_W = 6.9) is slightly higher than the 1986 (higher, M_W = 7.1) event, for all three recorded components. One could interpret this as a source effect (different focal depths). All these features could be also interpreted as a nonlinear behavior occurrence for the sedimentary soils subjected to strong seismic motion [5, 15].

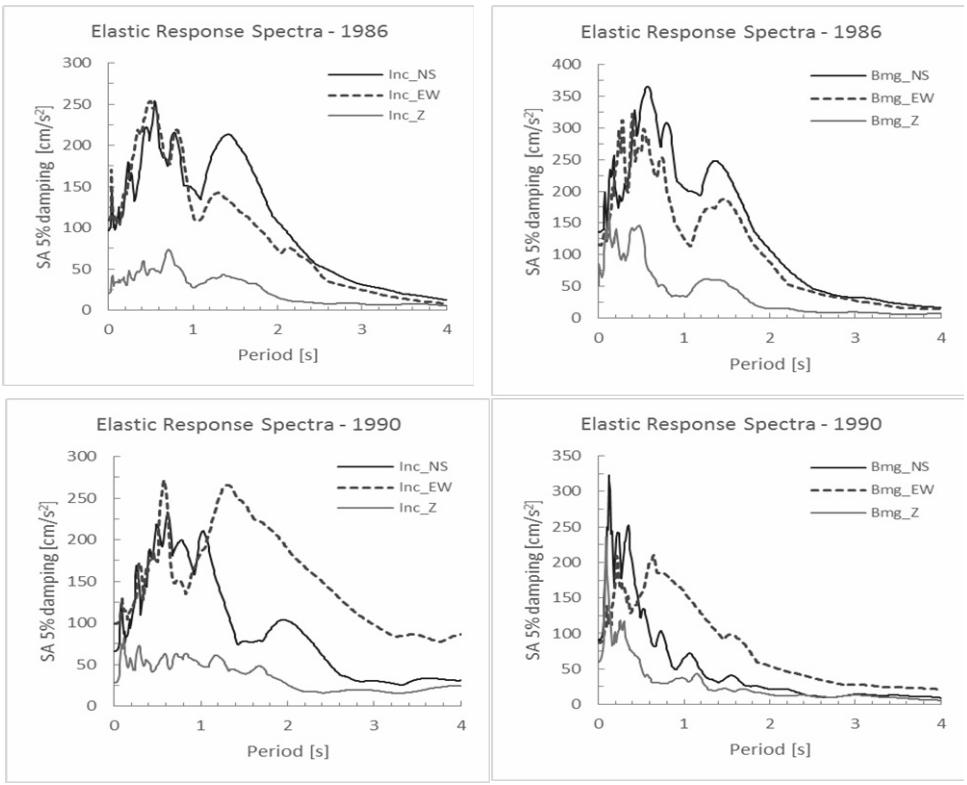

Fig. 7 – Response spectra for 1986 and 1990 events,
at two sites, INC and BMG.

4.2. FROM H/V COMPUTATION

An important database was obtained in the *National Institute for Earth Physics* (NIEP), consisting in accelerograms records for earthquakes of small magnitude, during the project *URbanSeismology* (URS) [6]. Continuous recording (24 hours / day) were carried out for 10 months (October 2003 – August 2004) in the above-mentioned project through international collaboration between the University of Karlsruhe – Collaborative Research Center 461 and NIEP.

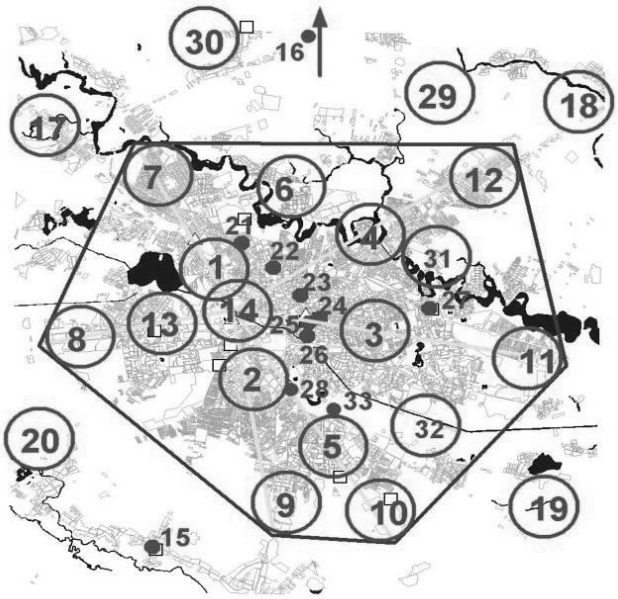

Fig. 8 – URS sites in Bucharest.

Recordings were made at 33 locations with seismic stations equipped with broadband velocity sensors (Karlsruhe BroadBand Array – Kabbala) uniformly placed on town territory and on the adjacent neighboring villages (Magurele, Voluntari, Otopeni, Popesti-Leordeni, Buftea, Surlari, Ciorogarla) (Fig. 8). In the above-mentioned period of time several earthquakes of various magnitudes occurred in Vrancea seismic region. Thus: 4 seismic events with $M_W > 4$, 48 seismic events with $M_W > 3$ and 67 seismic events with magnitude $M_W > 2$. The stations were located in public institutions, schools, parks, industrial areas etc.

The recorded waveforms of the URS experiment provided a rich and unique source for the study of the seismic wave field of a major urban region. Although the high noise level hampered a fast and simple data processing and analysis of seismic phases, receiver function sections demonstrate the ability to study the structure below the city of Bucharest. Furthermore, the noise itself can be regarded as a valuable seismic source for structural and hazard analysis in the earthquakes-prone capital of Romania.

A method that gives reliable data regarding the fundamental frequencies (periods) for soil deposits is so-called “H/V ratio”. The fundamental period obtained for the majority of sites is in accordance with already known results. By obtaining the fundamental period for more many and different spots situated in the Bucharest area we covered the zones where these data did not exist before. This

study is significant in seismic risk mitigation for the Bucharest city area, for a safer seismic design and for the improvement of microzonation efforts.

Seismic events selected for calculating the spectral ratio H/V from URS database are between M_W = 3.5 and 4.5. The average speed of a transverse wave above Fratesti layers has values between 340 m/s (in the southeast) and 390m/s at station TIT (Bd. Titulescu), in the North-West of the city. Due to this velocity structure, dangerous amplifications in the category of long periods can occur in this part of town at strong Vrancea earthquakes. Table 1 presents a comparison of the oscillation period for lithological columns for drilling F1 (Eastern Bucharest), F2 (downtown) and F3 (South Bucharest) (NATO Project SfP 981,882) calculated with the empirical formula $T = 4\ H/V_S$ (H is the thickness of the layers above the horizon, V_S is the Fratesti average transverse speed) and assessment of fundamental period with spectral ratio method H/V. H/V ratio was also calculated from noise recordings from the same area [7].

Table 1

Resonance period for lithological columns (fundamental periods in [s])

Drill	**Fundamental period evaluated with the method H/V [s]**	**Oscillation period calculated with the empirical formula $T = 4h/v_s$ [s]**	**Fundamental frequency calculated with the empirical formula [Hz]**	**Fundamental period calculated from ambiental noise [s]**
F1	URS08 = 1.45 URS13 = 1.5	1.42	0.703	1.38
F2	URS23 = 1.45	1.523	0.656	1.56
F3	URS05 = 1.48	1.39	0.717	1.42

Experimental observations argue method H/V. Comparing the results of the method H/V with other methods make us conclude that this method provides us with reliable data about sites [8, 9]. By obtaining the fundamental period for 33 sites situated in the Bucharest area we covered the zones where these data don't exist.

5. THE SITE OSCILLATION PERIOD DEPENDENCE ON STRONG EARTHQUAKES MAGNITUDE

A large dispersion of recorded natural period values happens when using many stations with different local conditions. INCERC is the only place in Romania where a large range of seismic movements were recorded from small to the strongest event of March 4, 1977 [10].

By using the formula, $T_g = 4\ H/Vs$, a unique oscillation period value is providing, irrespective to the earthquake magnitude. For describing the physical phenomena induced in the superficial layers by strong earthquakes, in the seismic waves

vertical propagation approach, several soil models can be used, but for Bucharest urban area the most suitable model is nonlinear viscoelastic. By using this method on thin or thick uniform layers of loess, clay, gravel with sand and marl, a nonlinear dependency of torsion modulus and dynamic damping values is observed. These features [10] depend only on material nature or type of soil, and are inducing local seismic effects. The study of dynamic parameters dependency on earthquake magnitude [12] shows that starting from magnitudes of Mw ~ 6, the nonlinear behavior starts to be important in the free surface seismic movement parameters evaluation, in local seismic hazard evaluation, especially for thick layers of tens of meters. In this sense, new approach was recently applied by Manea *et al.* (2016), [11] where a dependency of the resonance frequency in function of the *H* was derived at sites located in Bucharest area.

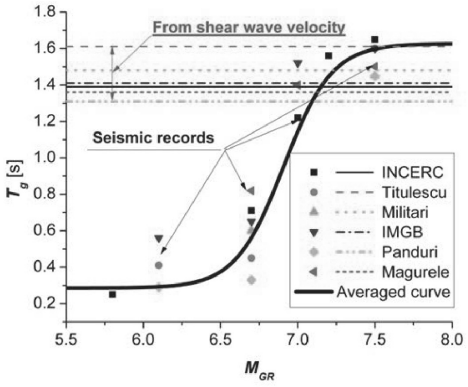

Fig. 9 – Nonlinear variation of oscillation periods with magnitude.

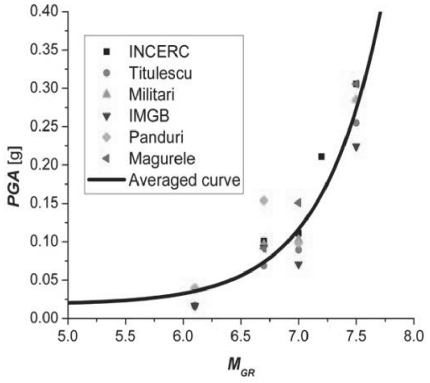

Fig. 10 – Nonlinear variation of PGA with magnitude.

From the recordings of the (strong) Vrancea earthquakes one can see a dependence of the site natural periods and *peak ground accelerations* (*PGA*) on magnitude, for packages of layers with different thickness at different earthquakes strength, as is illustrated by the examples given in Figures 9 and 10, where the data recorded at some Bucharest seismic stations is presented and the estimation of the maximum predicted event is added (M_W = 7.7).

6. SEISMIC RISK CONSIDERATIONS FROM SOIL – FOUNDATION – STRUCTURE INTERACTION PERSPECTIVE

In a soil-foundation-structure analysis the nonlinear behavior of the soil deposit under strong earthquakes action is a necessary way for a correct recommendation in buildings' construction. Under this approach one can obtain many essential

design data for the soil deposit and structure itself. Its effective application had a real enhancing in recent decades with the help of powerful computers, dedicated software and mathematical techniques.

In urban areas, the structures and their foundation, through their dynamic interaction produce a strong coupling between soil and structure. The impedance in the upper part of the foundation soils and medium bellow cause scattering of the incident waves. The waves that reach the structure are modified by its intrinsic properties, and the structure starts shaking with vibrating energy that is transmitted back into the ground (inertial soil-structure interaction) [13]. This soil-structure coupling manifests through horizontal motion of the building. The presence of structures modifies the site response and the nonlinear behavior of the soil in terms of frequency shift to the lower values. This effect appears to be important for rigid structures and not quite negligible for flexible structures. The soil nonlinearity is the parameter that influences the response of the building system. These effects are not negligible modifying the nonlinear response (in terms of frequency variation) between the free-field and urban-field, with smaller damping in the presence of structure. The nonlinearity observed for the building response is with the same order of magnitude as the variation of the soil response between the weak and strong motion. The nonlinearity of the soil reduces the shear wave velocity and increases its deformability. Hence, the soil nonlinearity partially controls the soil-structure interaction.

Building responses and structural deformations are essential in determining the seismic demand that is used in most of the earthquake resistance building codes (*e.g.* IBC-ICC 2000, Eurocode 8-CEN 2003, SNI-BSN 2002). In these codes, the shear force applied at buildings' base is computed by multiplying the building mass with corresponding response spectral (associated with building damping) at the fundamental period of the building. Stewart *et al.* (2002), [14] explained the role of *soil-structure interaction* (SSI) on the inertial interactions due to induced-base shear and motion relative to the free-field.

The essence of the strategy of avoiding site – structure resonance consists in the correct evaluation of the fundamental periods of both the structure T_s and the site T_g. The site materials exhibit a mechanical behavior dependent on strain, stress or loading level (expressed by dynamic stiffness degradation and increasing damping) [16]. In these circumstances, a dependency on the earthquakes amplitude must be considered, and this feature can be observed in the seismic records on different sites and can be modeled by the nonlinear Kelvin-Voigt model.

In the case of Vrancea earthquakes, it has been observed that only strong events (over $M_W > 7.2$) may lead to important structural damages. For a safe avoidance of resonance, it is practical to define for each site an oscillation period value range corresponding to strong earthquakes. For example, in the range of $M_W = 7.2 – 7.7$,

considered as destructive magnitudes for mostly extra-Carpathian urban areas in Romania, the highest value being the maximum expected magnitude, with assigned *PGA* values of approximately ~0.1*g* to 0.3*g*, the dangerous natural period range is between 1.22*s* up to ~1.65*s*, [4, 17] the recommendation is to avoid building up with these resonance characteristics.

7. CONCLUSIONS

An important database of earthquakes was obtained in recent years at National Institute for Earth Physics, for small magnitude earthquakes, recorded in the project URbanSeismology.

There are presented methods for computing the oscillation period of the soil and a short review for some matters regarding the behavior of the soil-structure systems under strong seismic movements. In this respect, we have used the only available record for the 1977 strong earthquake recorded at seismic station INCERC and this is the reason why we chose the same station to use its recordings for the 1986 and 1990 events, in order to compare the recordings on the same site.

We consider that the dynamic response of certain structures is strongly dependent of the ratio between the natural period of the structure and the dominant period of the emplacement site. Starting from information comprised by data bases for soils and buildings existing in Bucharest we selected the most relevant types of structural-sites systems in order to perform our study. This way we managed to draw a map of oscillation periods for Bucharest, Fig. 4. Having this map we know the dominant periods of every important zone in the city and we can judge if a building is suitable for such a zone, and the authors opinion is that it is more safe to pick the right building for a zone it suits than to force a non-resonance design in that place.

The effect of a soil deposit is one of filtering the input (seismic) motions, increasing their amplitudes in some ranges of frequencies (periods) and decreasing it in others.

The evaluation of the dynamic response of a soil deposit or a structure founded on soil requires knowledge of the stress-strain properties of the foundation materials.

The variation of the normalized period on excitation level $T_n = T_n(PGA)$ is obtained using interpolated data from resonant column tests. The method employed here was validated using recorded data from earthquakes. Using this approach, predominant period values can be predicted of sites for strong earthquakes, starting from small and moderate seismic events, which gives us a good possibility in mitigation of seismic risk for future buildings.

It is necessary to define for each site a natural period value range corresponding to strong earthquakes. For example, for INCERC site, in the range of $M_{GR} = 7 - 7.5$ with assigned *PGA* values of approximately ~0.1*g* to 0.3*g* the recommendation is to avoid designing buildings with natural period range between 1.22 up to ~1.65*s*.

Acknowledgements. This paper was partially carried out within Nucleu Program, supported by ANCSI, project numbers: PN 16 35 01 04, PN 16 35 01 07 and within Project *National Level of Risks Assessment* (RO-RISK).

REFERENCES

1. M. Dilley, R.S. Chen, U. Deichmann, A.L. Lerner-Lam, M. Arnold, with Jonathan Agwe, Piet Buys, Oddvar Kjekstad, Bradfield Lyon and Gregory Yetman, *Natural Disaster Hotspots: A Global Risk Analysis*, Synthesis Report, International Bank for Reconstruction and Development / The World Bank and Columbia University, 2005.
2. H.B. Seed, R. Murarka, J. Lysmer, I.M. Idriss, *Relationships of maximum acceleration, maximum velocity, distance from source, and local site conditions for moderately strong earthquakes*, Bulletin of the Seismological Society of America **66** (4), pp. 1323–1342, 1976.
3. C.O. Cioflan, A. Marmureanu, Gh. Marmureanu, *Nonlinearity in Site Effects Evaluation*, Romanian Journal of Physics **54** (9–10), pp. 951–963, 2009.
4. N. Mandrescu, M. Radulian, Gh. Marmureanu, C. Ionescu, *Integrate research of the geological, geophysical and seismological data for local response evaluation in Bucharest urban area*, Romanian Academy Publishing House, Bucharest, 2008.
5. Gh. Marmureanu, C. Cioflan, A. Marmureanu, *Cercetari privind hazardul seismic local (microzonare) al zonei metropolitane Bucuresti*, TEHNOPRESS, Iasi, 2010.
6. J.R.R. Ritter, S.F. Balan, K.-P. Bonjer, T. Diehl, T. Forbinger, Gh. Marmureanu, F. Wenzel, W. Wirth, *Broadband Urban Seismology in the Bucharest Metropolitan Area*, Seismological Research Letters **76** (5), pp. 574–580, 2005.
7. S.F. Balan, C.O. Cioflan, B.F. Apostol, D. Tataru, B. Grecu, *The resonance of the surface waves. The H/V ratio in the Metropolitan Area of Bucharest*, Eds. Santini, A., Moraci, N., 2008 SEISMIC ENGINEERING CONFERENCE COMMEMORATING THE 1908 MESSINA AND REGGIO CALABRIA EARTHQUAKE **1020**, pp. 207–215, Conference on Seismic Engineering Conference, Reggio Calabria, Italia, July 8–11, 2008.
8. H. Yamanaka, M. Dravinski, H. Kagamni, *Continuous measurements of microtremors on sediments and basement in Los Angeles*, Bulletin of the Seismological Society of America **83** (5), pp. 1595–1609, 1993.
9. E. Field, K. Jacob, *A comparison and test of various site-response estimation techniques, including three that are not reference-site dependent*, Bulletin of the Seismological Society of America **85**, (4), pp. 1127–1143, 1995.
10. D. Bratosin, B.F. Apostol, S.F. Balan, *Avoidance strategy for soil-structure resonance by considering nonlinear behavior of the site materials*, Rom. J. Phys. **62**, 808, 2017.
11. E.F. Manea, C. Michel, V. Poggi, D. Fäh, M. Radulian, S.F. Balan, *Improving the shear wave velocity structure beneath Bucharest (Romania) using ambient vibrations*, Geophysical Journal International **207** (2), pp. 848–861, 2016.
12. S.F. Balan, B.F. Apostol, *The Necessity of Considering Nonlinear Seismology in Site Evaluation*, 16-th International Multidisciplinary Scientific GeoConferences SGEM, doi: 10.5593/sgem2016B13, 2016.

13. B.F. Apostol, *A resonant coupling of a localized harmonic oscillator to an elastic medium*, Romanian Reports in Physics **68**, 116, 2017.
14. J.P. Stewart, D.H. Whang, P.J. Fox, J.W. Wallace, *Applications of UCLA NEES equipment for testing of soil-foundation-structure interaction*, Proc. 7th U.S. National Conference on Earthquake Engineering, Boston, MA, Paper 00018, 2002.
15. Gh. Mărmureanu, M. Misicu, C.O. Cioflan, S.F. Balan, B.F. Apostol, *Nonlinear Seismology – The Seismology of the XXI Century*, in Lecture Notes of Earth Sciences, Perspective in Modern Seismology, Springer Verlag, Heidelberg, 2004.
16. D. Bratosin, S.F. Balan, C.O. Cioflan, *Soils Nonlinearity Evaluation for Site Seismic Microzonation*, Proceedings of the Romanian Academy **8**, pp. 235–242, 2007.
17. C.O. Cioflan, A. Marmureanu, Gh. Marmureanu, *The quantitative evidence of the soil nonlinear behavior during of strong Vrancea earthquakes in real/nonlinear seismology*, Romanian Reports in Physics **63** (3), pp.839–851, 2011.