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# URBAN RESEARCHES FOR RISK MITIGATION IN BUCHAREST CITY AREA

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***Abstract***

*The paper analyses the behaviour of the soil/subsoil characteristics in the Metropolis of Bucharest under seismic movements with the goal of highlighting the potential damage induced by future strong events. For better understanding the specificity of seismic effects from earthquakes originating in Vrancea region were carried out several national and international research works to assess seismic hazard for Bucharest. Will be presented the last results of the 21st century research programs, with a lot of practical results: several drills in the most critical zones of the city, with hundreds of samples on which were done dynamic tests, static ones and downhole measurements for $v_p$ and $v_s$ profiles. An analysis of the continuously recordings by accelerometers was done, over the Bucharest area. The paper emphasizes the importance of the accumulated data for understanding the dynamic behaviour of the soil under Bucharest and how it influences the impact of future seismic hazards. Better knowledge of seismic hazard will lead to mitigation of building vulnerability to future seismic movements.*

***Key words****: geotechnical tests H/V ratio, seismic risk, Vrancea earthquakes.*

## INTRODUCTION

Romania is a country with a relatively high level of seismic hazard and in the perspective of a future strong earthquake the main risk-exposed area is Bucharest city (Dilley et al., 2005). With a continuously increasing building stock (of more than 131000 assets, 44% of them being constructed before 1963, according to 2011, National Census), it was more imperative the need of very useful information about structures for engineering community, in order to assess the structural integrity and also for authorities, in case of emergency after a strong earthquake.

Before the strong seismic event of 1977 design codes and studies were made, but these were not quit exactly in accordance to the constructed reality since there was no more major earthquake recording to reflect local characteristics of intermediate-depth events. The March 4, 1977 ($M_w$ = 7.4) earthquake had severely affected almost the whole outside area of the Carpathians Arch. In the capital city, Bucharest, as well as in other areas, seismic intensity exceeded with one grade and more the intensity existing in seismic norms at that time. The damages consisted in 25 residential blocks that collapsed (in downtown Bucharest), 3 were demolished after being heavily damaged and 100 had serious damage with the necessity for emergency rehabilitation.

After this situation there was a complete change in perception about earthquakes, reflected in codes and studies about effective seismic risk mitigations measures. Still, nowadays in Bucharest there are more than 40000 buildings erected before 1940, which raises concerns about their safety in future strong seismic events.

The paper offers the possibility to conduct basic research on the urban seismic wave field as well as to perform combined structural and hazard analysis for Bucharest. The knowledge of soil layers content underneath the Bucharest surface is an important step in performing a complete analysis of the seismic hazard in Bucharest. These goals could be attained with highly costs. To achieve these, in the early 21st century, cooperation programs were undertaken with the Collaborative Research Centre (CRC461) "Strong Earthquakes" at the Universität Karlsruhe (TH), Germany. As part of these programmes common seismological experiments were conducted in Romania. Especially in Bucharest, high-quality seismic data were acquired during the URS (URban Seismology, 2003/3004) Project. Within this project 32 state-of-the-art broadband stations were continuously recording in the metropolitan area of Bucharest for 10 months (Ritter et al., 2005).

Following, a NATO international programme was launched through were performed drillings on the city area followed by different tests. A homogeneous dataset of geotechnical parameters of the soils and rocks of the uppermost layer's underneath Bucharest were obtained and used to complete seismological measurements across the city. The paper presents the data obtained from boreholes and the analysis of data continuously recorded by accelerometers, over the Bucharest area. An analysis of the soil amplification and spectral response was performed, and a method for computing the oscillation period of the soil is presented, applied to city area.

## MATERIALS AND METHODS

### *Geological data about Bucharest*

Bucharest, the capital of Romania, with more than 2.5 million inhabitants, is considered a highly-most earthquake-endangered metropolis in Europe. All disastrous earthquakes are generated within a small epicentral area – the Vrancea Source - about 160 km North-East of the Bucharest (Figure 1, Balan et al., 2014).

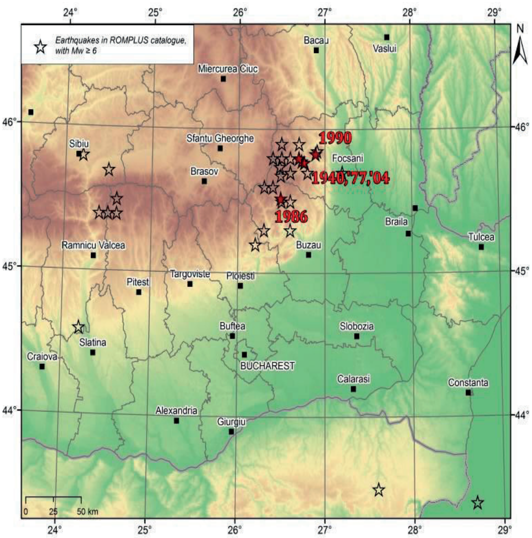


Figure 1. Major earthquakes ($M_w \geq 6$) described in the ROMPLUS Catalogue, and the location of Bucharest

The city of Bucharest is built on young, partly unconsolidated and water-saturated sediments of the Dambovita and Colentina river systems and their surrounding plains. Dambovita valley appeared like a long corridor approximately 22 km long. Its width varied from 650 m, in some places in the centre of the city, to about 4 km at its eastern exit, before being regularized in the last century (Mihailescu, 1924). Also, there are lakes in the city. For example, one of them, the lake "Lacul Morii" (the Lake of the Mill) is an unusual feature, formed by the man-made dam on river Dambovita in the 20th century.

Geological, geotechnical and hydro-geological drillings in the city have made it possible to know what is included in successive subsoil deposits (Ciugudean-Toma et al., 2007).

The Quaternary geology of Bucharest City is characterised by seven sedimentary layers (complexes), with different lithology, geotechnical characteristics and variable thicknesses (Mandrescu et al., 2007; 2008). The unconsolidated sedimentary layers in the area of Bucharest amplify the seismic shear-waves which may cause severe destruction (Cioflan et al., 2011; Manea et al., 2016). Thus, disaster prevention and mitigation of earthquake effects is an issue of highest priority for Bucharest and its population.

### *Geophysical and geotechnical methods for surveying the subsoil of Bucharest*

Along the year's numerous geotechnical drills, geophysical measurements, geotechnical tests, etc., were done for analysing the role of the subsoil, beneath the capital for a correct appreciation of the hazard due to the strong earthquakes which affected the city in the last centuries.

Especially in Bucharest, high-quality seismic data were acquired, obtaining a useful and diverse dataset providing important information on the seismic amplitude variation across the area. The site studies have a major contribution to the mitigation of seismic risk. In this concern, the continuously monitoring of the buildings, which offer data from the micro tremors, vibration and the noise, seismic or non-seismic, prove to be useful (Balan et al., 2019; Dragomir et al., 2019).

One of the most important elements in hazard evaluation of Bucharest zone is a modern ground acceleration network which has been upgraded in the last years up to over 23 stations (and 160 seismic stations in Romania - National Seismic Network of National Institute of R-D for Earth Physics) with easy handling data (accelerations/velocities easy to transform in displacements). A dense network is needed in order to identify seismic events and compute correlation functions between the recorded ground deformation and a seismic movement.
Within the URban Seismology Project (URS) which was a joint achievement between the Collaborative Research Centre 461 (CRC461) at the University of Karlsruhe, Geophysical Institute, and the National Institute of R-D for Earth Physics (NIEP) in Bucharest. The aim was to measure seismological broadband waveforms in the city area of Bucharest. Continuous mode recording at 32 sites with broadband sensors, sampling rate 100 Hz (which allows us to study signals of up to 50 Hz), with GPS time synchronization and removable 6.4 GB hard disks, on 3-6 channels was achieved for 10 months. These data are the basis to verify predicted site amplification effects as well as other research topics (Figure 2).

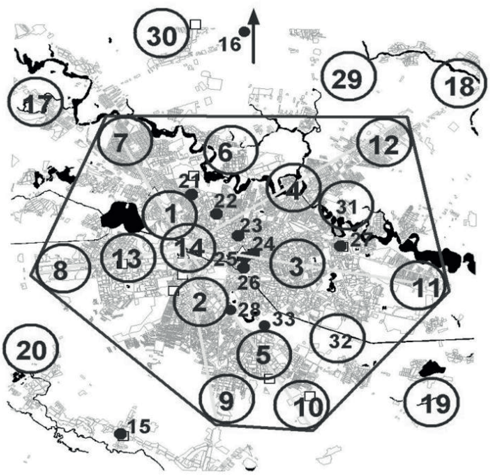


Figure 2. URS sites in Bucharest
(URban Seismology Project)

The recorded waveforms of this experiment provided a rich and unique source for the study of the seismic wave field and the structure within a major urban region (Figure 3).

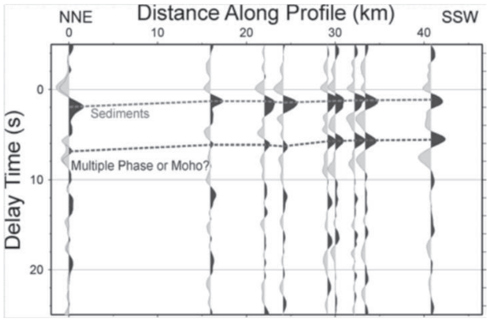


Figure 3. Receiver function sections across the metropolitan area of Bucharest from NNE (URS06) to SSW (URS07). Stack of up to 8 tele seismic RFs filtered from 0.083-0.5 Hz with two correlated phases (Ritter et al., 2005)

Another extended program was NATO Project “Site-effect Analyses for the Earthquake-Endangered Metropolis Bucharest, Romania” (NATO SfP Project No. 981882, 2008). The aim of the project was to gather more geotechnical and geophysical data to fill gaps between already existing data about the subsoil of Bucharest.

***Data gathering and processing***

To acquire basic data for subsoil layers in a homogeneous way, from unexplored zones, were selected 10 boreholes in Bucharest area. At these boreholes were done seismic measurements and geotechnical analysis of the core samples. From these we determined representative dynamic parameters of the soils and rocks. These dynamic parameters were used as input for linear and non-linear waveform modelling to estimate the seismic amplitude amplification at specific sites in Bucharest. These modelled waveforms were compared and calibrated with observations from seismic stations in the city. The results from the site-effect analysis were gathered in an updated seismic micro zonation map of Bucharest (Marmureanu, 2016)
One important component of engineering seismology is to evaluate the role of the near-surface soil layers. These layers, on which buildings and other constructions exist, can have a wide range of influences on the ground

shaking. For example, loose soils or sediments can amplify the ground motion or water-saturated sediments can produce soil liquefaction. These phenomena can then cause complete yielding of the ground during earthquake shaking with the result of catastrophic collapse of building. This underground is especially prone to strong shaking and even amplification of earthquake waves including resonance and ground liquefaction.

Therefore, the specific overall goal of the NATO project was to obtain a homogeneous dataset of geotechnical and geophysical parameters in the shallow (< 100 m), unconsolidated soil and sediment layers. Its accomplishments consist in: 10 new 50 m deep boreholes, were drilled in the metropolitan area of Bucharest (Figure 4). Complete lithological profiles with about 250 recovered core samples for geotechnical analysis were gathered in order to recover sample cores for static and dynamic tests and to measure vertical seismic profiles. The 10 boreholes are placed near existing seismic station sites to allow a direct comparison and calibration of the borehole data with actual seismological measurements. At all ten boreholes were conducted downhole measurements for $v_p$ and $v_s$ profiles.

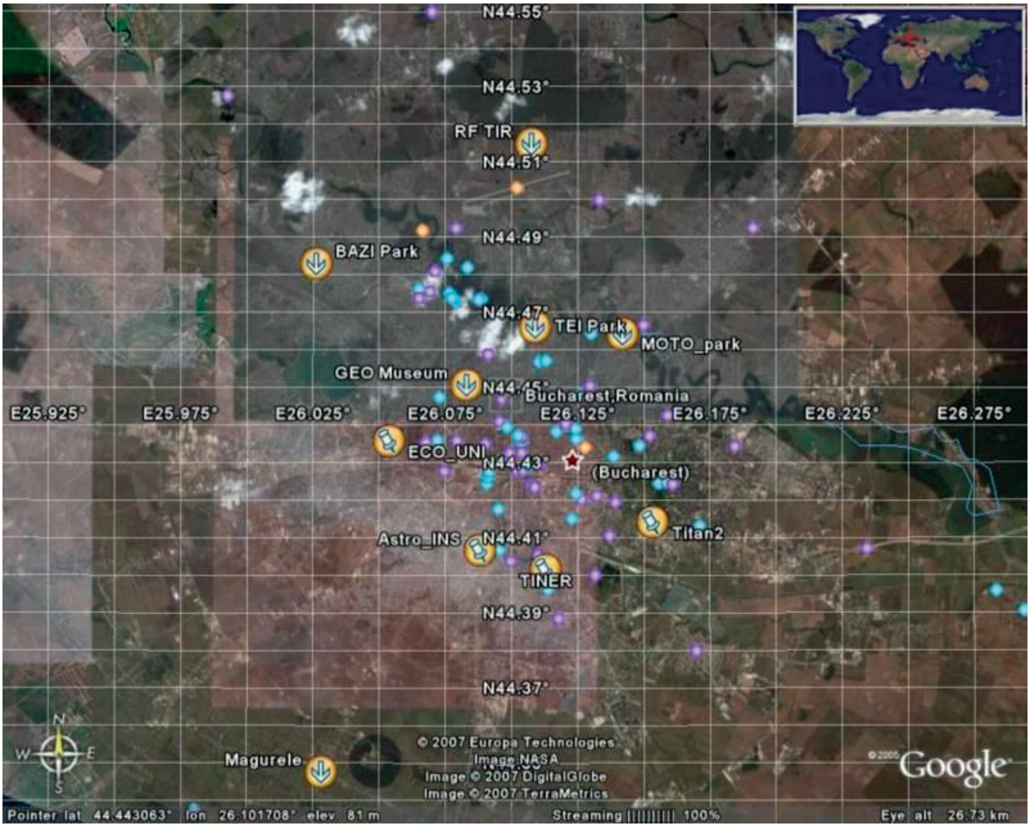


Figure 4. Map of the Bucharest City area with location of the 10 boreholes (NATO SfP Project, 2008).

The 250 soil and rock samples from the drilling sites 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 subjected to geotechnical tests (static and dynamic) with the help of resonant columns and dynamic triaxial.

With all these data were performed seismic analyses. Here is presented one of them, which allows to obtain fundamental period of the soils deposits by H/V ratio method. This ratio gives us not only information about resonance period but also on the corresponding amplification, sustained by numerous studies (for example Balan et al., 2008; Grecu et al., 2008) showing that the H/V ratios with peaks around fundamental frequency corroborates to the surface soft soil strata where exists an emphasized impedance from more rigid strata situated below.

The seismic events chosen for the H/V spectral ratios computation were selected by taking into account the recordings quality and the magnitude higher than 3.5. They belong to a data base which consists in events recorded in the time period of interest (source: ROMPLUS, "Romanian Earthquake Catalogue"). The H/V ratios computations were performed with J-SESAME software program for the noise and with "H/V-ratio" software for the seismic events (developed by Oncescu et al., 2007). This J- SESAME software program was advanced in the frame of European SESAME Project (Site Effects assessment using Ambient Excitations). The spectral ratios are computed for seismic events and for noise, at each seismic station, as shown in the Figure 5, denoted by the name of the station. The spectral ratio curve is period-dependent. The dashed lines are the root mean square (rms) of the H/V ratio. The average shear wave velocity for the layers above Fratesti has values between 340m/s (in the South-East) and 390 m/s in the North-Western part of the city (results obtained through down-hole computation) (Mandrescu et al., 2007; Bala, 2009; Bala et al., 2009).

The geological structure (Mandrescu et al., 2000; Moldoveanu et al., 1999), corresponding to the deep sedimentary formation of the city, was compiled as a simplified model, and employed to obtained a velocity structure together with quality factors. This information corroborated with the spectral ratio data, obtained from simulation of the seismic movement as corresponding to stronger events could indicate that dangerous amplifications in the long period range could be expected in this city area in case of strong Vrancea earthquake (Cioflan et al., 2009; Apostol, 2008).

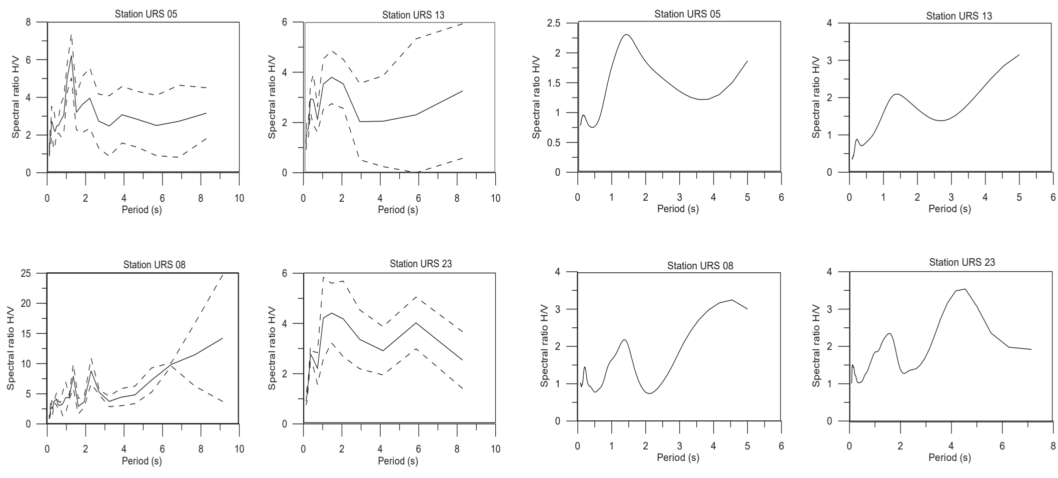


Figure 5. The spectral ratios H/V computed for the URS05, URS08, URS13 and URS23 seismic stations: (a) for seismic events and (b) for noise

This technique provides realistic estimates of spectral amplifications and can supply, when necessary, the lack of strong motion recordings for the "target" site.

The used method makes it possible to obtain at low cost and exploiting large quantities of existing data (e.g. geotechnical parameters, surface geology data, seismological data), a realistic seismic input at surface.

These data set can be fruitfully used by civil engineers for designing new seismo-resistant constructions.

## RESULTS AND DISCUSSIONS

From geophysical-geotechnical processing:

- The aim was to measure seismological broadband waveforms in the city area of Bucharest.
- Continuous recording at 32 sites with broadband sensors, sampling rate 50 Hz, 3 channels, have offer a powerful database (between Oct. 2003-Aug. 2004) that is the basis to verify predicted site amplification effects as well as other research topics.
- 10 new, 50 m deep, boreholes were drilled to recover samples for geotechnical laboratory tests and to measure in situ seismic velocities profiles, $v_p$ and $v_s$.
- Soil samples were processed with the help of resonant columns and dynamic triaxial equipment (see Table 1).
- Were performed 400 geotechnical analysis of samples from 6 Quaternary layers, improved $v_s30$ mapping, spectral amplification curves for the 10 sites and investigation of seismological measurements across the city.
- Was obtained a unique, homogeneous dataset of soil-mechanic and elasto-dynamic parameters of the subsurface of Bucharest.

Table 1. Geotechnical tests (selection) for the 10 sites

| Operation | Number | Objective |
|---|---|---|
| Drilling | 10 boreholes | Drilling and Probing Operations |
| Resonant column tests | 58 | Dynamical parameters for linear and non-linear modeling |
| Triaxial tests (dynamical, undrained); edometric tests, maximum and minimum compactness | 15 | Dynamical and mechanic parameters |
| CU Triaxial test | 4 | Standard geotechnical experiment |
| Angle of repose | 11 | Standard geotechnical experiment |
| Granulometry | 54 | Standard geotechnical experiment |
| Maximum and minimum compactness | 6 | Standard geotechnical experiment |
| Determination of e_min and e_max | 11 | Standard geotechnical experiment |
| Determination of liquid and plastic limit | 4 | Standard geotechnical experiment |

- A comparison and calibration of the borehole data with actual seismological measurements.
- This researcher helped to develop an optimized seismic micro zonation of the metropolitan area of Bucharest which can be implemented for the future urban planning.

From H/V measurements:

Table 2 presents a comparison of the fundamental period of the soils package from lithological columns from drills F1 (Eastern Bucharest), F2 (downtown) and F3 (South Bucharest) (NATO Project SfP 981882) calculated with the empirical formula $T = 4\ h/v_s$ ($h$ is the thickness of the layers, $v_s$ is the average transverse waves velocity) and assessment of fundamental period with spectral ratio method H/V. The drills are in the vicinity of seismic stations URS05, URS08, URS13 and URS23 for which was computed the spectral ratios for seismic events and noise.

## CONCLUSIONS

This database is a valuable collection of elastic and dynamic parameters of the Quaternary sedimentary layers obtained by direct and indirect measurements, and it was continuously updated during recent projects (BIGSEES and POSEIZON) with much more processed records for significant earthquakes after year 2008. The paper emphasizes the importance of the accumulated data (geotechnical, geophysical and seismological) for understanding the behaviour of the soil under Bucharest at last seismic events and how it will influence the impact of future seismic hazards.

The seismic hazard assessment combined with local effects evaluation ensures the local seismic hazard coherency as important steps in risk mitigation process, through a realistic structural seismic response, that could be used for improving design norms.

Table 2. Calculation of fundamental periods of sites

| Drills | Fundamental period evaluated with the method H/V [s] | Fundamental period calculated with the empirical formula $T$=4 $h/v_s$ [s] | Fundamental period calculated from ambiental noise [s] |
|---|---|---|---|
| F1 | URS08 = 1.45<br>URS13 = 1.5 | 1.42 | 1.38 |
| F2 | URS23 = 1.45 | 1.523 | 1.56 |
| F3 | URS05 = 1.48 | 1.39 | 1.42 |

However, all the data collected on seismic hazard and buildings behaviour during medium earthquakes were discussed with researchers and designers for planning measures for rehabilitation of old buildings and construction of safe ones.

These research programs helped to develop an optimized seismic micro zonation of the metropolitan area of Bucharest which could be implemented for future urban planning.

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