INVESTIGATIONS OF THE SEISMIC SITE RESPONSE FOR SAFER URBAN ENVIRONMENT

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Abstract. The seismic response and local seismic effects are analysed in terms of spectral accelerations, peak ground acceleration (PGA) and site's oscillation periods for city of Bucharest. By means of these parameters we may characterize the seismic hazard generated over the city area by Vrancea intermediate-depth seismic source. A data set consisting of the available seismic recordings is used for the last strong Vrancea earthquakes ($M_w > 6.4$). Also, the geological description and interpretation of data contained in detailed geological maps is employed as the main and most basic information necessary to perform such an investigation. The existence of down-hole data complements the geological information. The necessity of defining a dominant period-value range corresponding to seismic movements for each site is highlighted, by comparing some terrain characteristics induced by strong events (acceleration, response spectra, oscillating period of the superficial soil deposit) and their changes related to the magnitude of the earthquake. Despite the fact that seismic effects may not be characterized entirely by critical values in the range of the nonlinear effects, the particular geological features of the Romanian capital Bucharest may induce various amplifications, as a response to major earthquakes. These data about soil deposits behaviour could be used as input data for seismic risk mitigation. They provide an important contribution, in a very effective way, to getting solutions toward a safer seismic design.

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

1. INTRODUCTION

The present study is focused on Bucharest Metropolis foundation soils, where buildings are placed in an area exposed to high seismic hazard. Bucharest, the capital of Romania, with more than 2 million inhabitants, is considered a high earthquake-endangered metropolis in Europe. The city suffered four major earthquakes with moment magnitudes (M_w) between 6.9 and 7.5 that hit Bucharest in the last 80 years. The most recent destructive earthquake of March 4th, 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 40 × 80 km large, with focal depths in the range ~90–150 km.

Bucharest is located on thick Quaternary deposits (thickness greater than 250–300 m), which are part of the Moesian Platform at an average epicentral distance of about 100–180 km from the seismic Vrancea region. Taking into account the city location new information about geophysical bedrock depth of the Moesian Platform and adjacent area was obtained using wave-field data [1]. The near-surface geology of the city consists of deep sedimentary and soft deposits, with thickness that vary from north to south [2]. A velocity model based on geophysical measurements [3], reveals soft soil conditions (shear wave velocities $v_s < 360$ m/s) of several tens of meters that underlain layers of stiffer soils ($v_s > 360$–700 m/s) with depths of several hundreds of meters. These characteristics are known to cause significant amplification of the earthquake shaking [4–6].

Studies on the local effects for Bucharest city area had been carried out by [2, 3, 7–10]. These effects are described in terms of transfer functions (or spectral amplification ratios compared to a reference station). For the particular case of induced effects coming from intermediate Vrancea earthquakes vertical waves propagation models were used, calibrated by means of local existing seismic records [7, 11, 12]. Physical and numerical models used in these approaches are then employed for the "maximum possible" event or expected earthquake scenario. 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 [13, 14]. An attempt for seismic zonation must take into account the local site condition and the potentially nonlinear behaviour.

Therefore, the local soil characterization together with the local seismic responses play a decisive role in determining the local effects under seismic excitation. Detailed geometry of layers and evaluation of linear and nonlinear properties of all types of soils are necessary for an appropriate analysis [15–17]. These include, in the first place, a description of the geological environment and lithology, then soil density, the presence of water content, and finally the various moduli of elasticity and damping ratio as a function of the shear strain. The detail of the analysis depends on the objectives and on the capacity to gather information.

In many cases, given the lack of available data to perform urban site studies, one must include surveys for obtaining some of this basic information. In this way, preliminary results and maps issued during this process can be of a high value themselves for their possible use in other applications. Examples of these intermediate products are maps with geotechnical information, potential active faults, topography and underground local characteristics. The existence of down-hole data complements the geological information. The more convenient situation as far as gathering the best information on soil strata would be to have the deeper down-hole information for the larger geographical extension. The regional and municipal regulations may detail and modify national codes with results from microzoning. Further, site-specific

studies are needed for the design and construction of important engineering structures, as well as for performing safety analysis of existing important vulnerable structures.

In this paper some optional site studies are presented that may be proved to be important for social and economic constructions. The authors intend also to point up the soils characteristics (specificity) and their effects upon constructed environment in Bucharest city area. Site oscillation period and peak ground acceleration (PGA) dependence on magnitude will be analysed taking into account different earthquakes in Romanian territory. It is highlighted the necessity of defining a dominant period-value range corresponding to such movements for each site by comparing some characteristics induced by strong events (such as acceleration, response spectra, oscillation period of the soil deposit) and how they are changed by the magnitude of the earthquake. Therefore it could be said that, despite the fact that seismic effects may not be characterized entirely by critical values in the range of the nonlinear effects, the specificity of the features in the Romanian capital superficial soils may induce various amplifications. The seismic response due to the particularity of the sedimentary alluvial basins underneath Bucharest area may induce various amplifications. This phenomenon was illustrated in developing microzoning maps in terms of PGA with the corresponding oscillating soils periods [8, 18]. By knowing the dominant periods over the Bucharest area one could estimate if a building is suitable or not for a specific site.

2. VRANCEA EARTHQUAKES SEISMIC CHARACTERISTICS

2.1. CHARACTERISTICS OF SOIL DEPOSITS RESPONSE

In this section we focus on the sites response using recording data. In order to better characterize and understand the seismic wave field produced by earthquakes in the area of Bucharest, a time-frequency analysis has highlighted the generation of low frequency surface waves (< 1 Hz) for sufficiently strong or superficial events. This phenomenon could be explained by the influence of source mechanism (radiation pattern, directivity effects), geological layering and geometry of the local structure [1, 19]. The soft Quaternary sediments under Bucharest city would be responsible for the decreasing in wave velocity in these superficial layers and for absorbing high frequencies; therefore high fundamental periods [8], area are observed throughout the city. In fact one can notice that there is an increasing tendency of natural period with increasing the magnitude. In Figures 1 and 2 is presented a comparison between response spectra at several locations for moderate to strong earthquakes that produced no damage over the city area.

We note that very slightly different values for the oscillation period are attained over the city, at each magnitude, for certain strong earthquakes. In fact, the oscillation period values are distributed over a certain range, with a little increasing

tendency with magnitudes, at each considered site. These values are not over 0.5 s for the 1990 event ($M_w = 6.9$, blue line) and slightly above this value for the 1986 event ($M_w = 7.1$, red line). An exception is encountered at one station, MTR, where these values are clearly much higher, with T_0 around 1.5 s for 1986 event. There, the lower value, around 0.3 s is for the smallest earthquake (1990 second event, $M_w = 6.4$, green line). When a comparison is made with the strongest recorded earthquake (1977 event, $M_w = 7.4$) it is observed an obvious shift of the oscillation periods towards higher values, around 1.22 s (Figure 3). This typical seismic response, at stronger magnitudes, could also suggests that nonlinear effects may influence this behaviour for sites natural period [14].

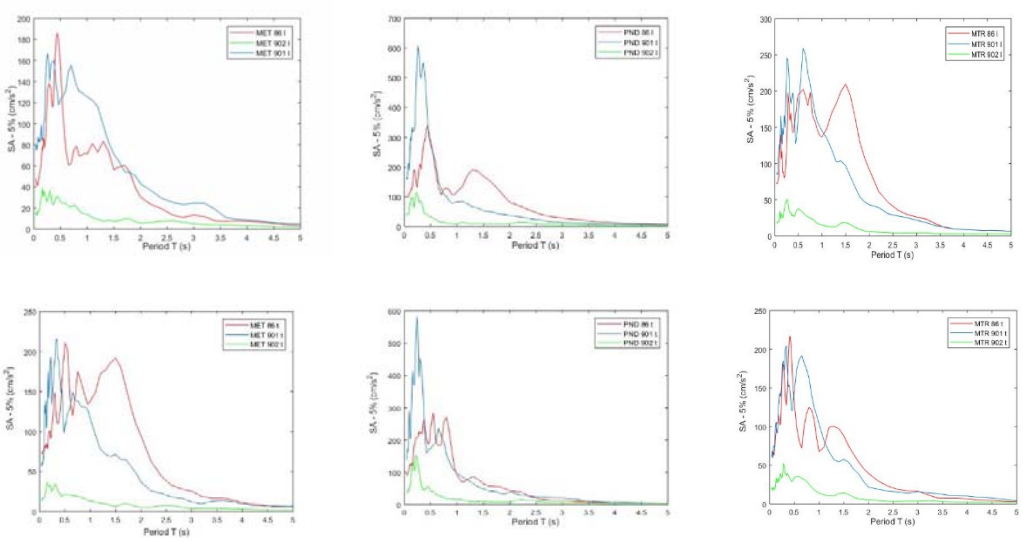

Fig. 1 – Acceleration response spectra for three earthquakes: 1986 (M_w=7.1), 1990 I (M_w=6.9), 1990 II (M_w=6.4) for the longitudinal component (l, upper panel) and transversal component (t, lower panel), at three seismic station (Color online).

Figure 3 shows the acceleration response spectra for earthquakes of March 4, 1977 ($M_w = 7.4$; $T = 1.22$ seconds), August 30, 1986 ($M_w = 7.1$; $T = 0.56$ seconds) and May 30, 1990 ($M_w = 6.9$; $T = 0.47$ seconds), recorded at station INCERC Bucharest (a location in Bucharest city area) on NS components and the fraction of critical damping $\zeta = 5\%$ [9].

The lack of recorded data, especially for the stronger earthquakes, together with the lack of knowledge about the weight (amplitude) of the typical local effects, are the main obstacles that need to be overcome for a sound conclusion upon relevant assessment of the site effects evaluation in the city area. A solution to complete these studies could be the computation of the synthetic accelerograms.

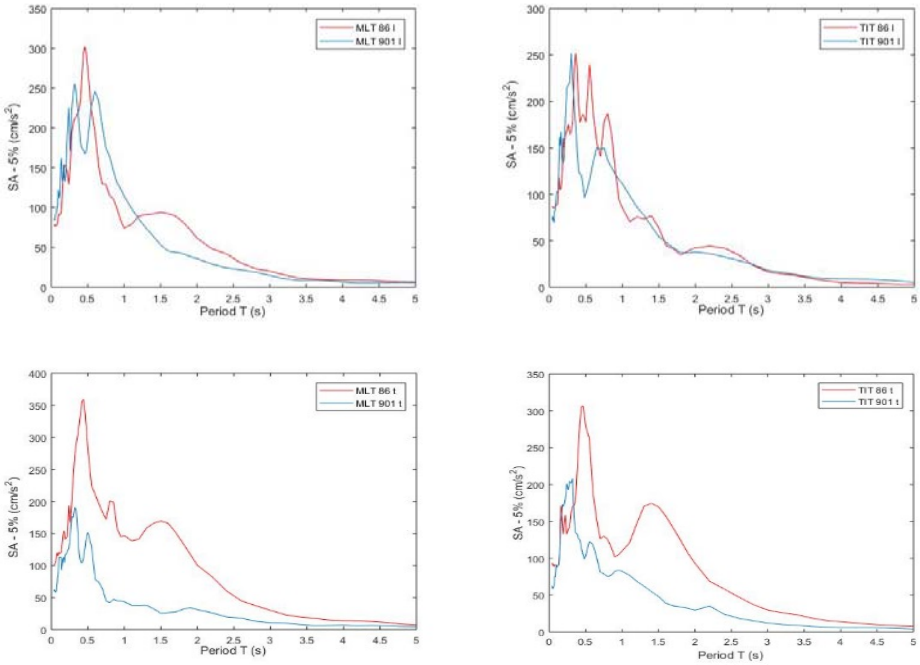

Fig. 2 – Acceleration response spectra for two earthquakes: 1986 (M_w = 7.1), 1990 I (M_w = 6.9), for longitudinal component (l, upper panel) and transversal component (t, lower panel), at two seismic station.

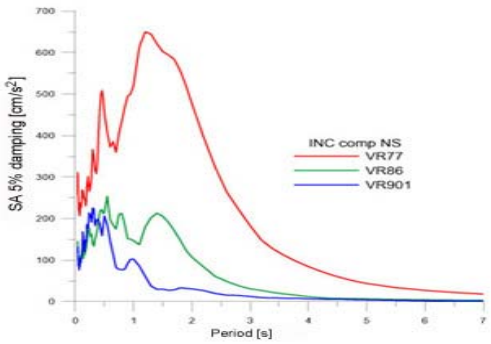

Fig. 3 – Acceleration response spectra for three seismic events (including the strongest recorded one): 1977 (M_w = 7.4), 1986 (M_w = 7.1), 1990 (M_w = 6.9) at INCERC station (*source*: Cioflan *et al.* 2011).

An important work in this direction was carried out by a method that takes advantage of computing excitation movements of layers from the local structure, including the determination of the local seismic response to vertical propagation of seismic waves. Simulations calibrated for at least one station allow us to evaluate

the seismic response in places where the seismic recordings are lacking, a very important fact in local seismic hazard studies for Bucharest city. The computation were performed for five real recorded seismic events with moment magnitude values between 6 and 7.4, and one simulated earthquake, with $M_w = 7.7$ *i.e.*, a maximum expected one [20]. It was shown that important amplification are encountered over the city area, but the decreasing of the amplification ratios with the increasing magnitude is observed. This inversely-proportional dependence of the local effects on the earthquakes magnitude is characterized also by a nonlinear variation tendency.

2.2. CONSEQUENCES OF THE SOIL DEPOSIT PREDOMINANT PERIOD VARIATION WITH MAGNITUDE

Previous analyses show no tendency of dependence of the spectral amplification on site location, but rather a slightly random variability [21]. The relatively uniform geology within the same layers extends over the entire city area [8]. In the view of what have been stated above from the local response observation, just a correlation between the thickness of the Quaternary cohesionless deposits and its predominant period could be implied. However, the important role of the Quaternary deposits was confirmed in previous works done some long time ago (see, for example [22–26]).

Such a result may indicate that different magnitudes excite soil sedimentary strata with different thickness, therefore generating a different response [18, 27]. Hence, the variation of the natural period values has an important role in the occurrence of resonance phenomenon for certain buildings. But at the same time only strong events (over $M_w = 7.2$, in Vrancea source) may lead to significant structural damages [9]. In order to safely avoid resonance, it is therefore necessary to define natural period values ranges for each site corresponding to strong earthquakes. In the range of $M_w = 7.4$–7.7, which are considered to be highly destructive magnitudes (the highest value being the maximum expected magnitude), corresponding to Vrancea earthquakes, with assigned PGA values of approximately over ~0.2 g and dangerous natural period range between 1.22 s up to ~1.65 s (for INCERC site) [28], the recommendation is to avoid constructing buildings with these resonance characteristics. When medium earthquakes were considered, the period values are distributed, but just over rather a narrow range, while keeping the magnitude-increasing tendency (see also Figures 1 and 2, for different other sites). Table 1 presents these characteristics (for another three medium seismic events) together with additional information about the Vrancea earthquakes (Figure 2) and their characteristics such as the PGA, T_0, the natural period of the seismic records for the same INCERC site.

These values could be an indication that the natural periods vary directly proportional with magnitude for different earthquakes as the PGAs increase (for the discussed area *i.e.*, Bucharest city).

Table 1

Natural periods at INCERC site for different PGA (different seismic events)
(Marmureanu *et al.*, 2016)

Event	M_w	PGA (g)	T_0 (s)
27.09.2004	4.6	0.008	0.15
18.06.2005	4.9	0.011	0.18
27.10.2004	6.0	0.014	0.22
30.05.1990	6.9	0.067	0.47
30.08.1986	7.1	0.097	0.56
04.03.1977	7.4	0.207	1.22

3. SOIL VARIABILITY

Focusing now on the rocks behaviour under strong seismic loads, we could see the nonlinear behaviour of the soil compounds. Such a situation may appear for strong earthquakes, like those experienced by Bucharest city in the last 80 years [9]. In order to substantiate the manifestation of the nonlinear behaviour we may admit that deformation in a soil deposit increases as the level of stress goes up due to earthquake magnitude affecting the site [9, 14]. This phenomenon could induce non-linear behaviour in soil strata as a function of strain level. Further, changes could appear in the mechanical properties of the soil layers, expressed by their dynamic response during strong seismic movements. A proof for nonlinear response of soils influencing the local site conditions, at strong magnitude, could be obtained by using the *spectral amplification factors* (SAF) [14, 18], applied for areas with thick Quaternary sediments.

The observational data for three strong earthquakes [20, 21], make possible to present mean values of spectral amplification factors for three strong earthquakes from XX^{th} century (see Table 2) computed at several locations in the Bucharest city area. Higher values for decreasing magnitudes may suggest that nonlinear effects occur.

Table 2

Spectral amplification factors for acceleration and velocity for three strong Vrancea earthquakes

Damping	August 30, 1986; M_W= 7.1		May 30, 1990; M_W= 6.9		May 31, 1990; M_W= 6.4	
β%	$(SAF)_a$	$(SAF)_v$	$(SAF)_a$	$(SAF)_v$	$(SAF)_a$	$(SAF)_v$
2%	4.74	3.61	5.58	3.72	6.22	4.84
5%	3.04	2.69	3.98	2.95	4.76	3.48
10%	2.43	2.99	2.56	2.14	2.92	2.69
20%	1.78	1.5	1.82	1.58	2.13	1.86

Therefore, the spectral amplifications factors technique allow us to conclude that a nonlinear behaviour should be considered, experienced during strong earthquakes, in accordance with the data recorded at different locations.

In supporting these statements, as follows from the soil dynamics experiments, shear modulus G and damping D become functions of strain level γ, and the nonlinear behavior could take place.

This is another hint that the constitutive relationships stress-strain will be nonlinear, therefore nonlinear viscoelastic laws are requested and the suitable model employed in this situation is of the nonlinear Kelvin-Voigt-type model [9, 29–31]. Moreover, as a continuation of these experiments, involving laboratory data processing, we may estimate a nonlinear dependence of the natural site period in terms of loading [32]. It appears that the soil response is nonlinear over a certain level of deformation, with implication on site oscillation periods variability.

4. DISCUSSION AND CONCLUSIONS

This paper intends to raise awareness through emphasising topics about important facts in the design of constructions – the site study, in the case of important investments or rehabilitation of old structures. The site response characteristics are specific to the Vrancea seismic source (crustal intermediate-depth) and the soil in the Romanian Plane, but it is not excluded to be found also in other regions. A good knowledge of properties of the foundation soil gives the guarantee of a safe design, in a seismic zone. The authors present a way of interpreting the seismic response and local seismic effects, especially for sedimentary soil structures, responsible for the seismic hazard generated by intermediate depth seismic sources. It combines information for layers underneath the urban area of the Bucharest city with the determination of the local seismic response to vertical propagation of seismic waves through these media. The earthquakes considered are those produced in the seismic region Vrancea. Since the effect of a soil deposit can be regarded as filtering the input (seismic) motions, increasing their amplitudes in some ranges of frequencies (periods) and decreasing it in others, the determination of the local seismic response to vertical propagation of seismic waves should take into account the nonlinear effects induced by strong seismic excitation of the local geological materials. The verification of the results should succeed at a satisfactory level, for the purpose of engineering seismology, for intermediate depth earthquakes (60–150 km) in a frequency domain up to 2 Hz. The range of frequencies 0.05–4 Hz includes, practically, all the seismic excitations capable of inducing damages in buildings.

A discussion is included here on some characteristics induced by strong events (such as PGAs, response spectra, oscillation period of the soil deposits) and how they change accordingly to the magnitude of the earthquake. The typical seismic response, at strong magnitudes, consists in a shift of the soil oscillating periods as magnitude increases. We should specify that, for the Bucharest city, the important damages and casualties occur for magnitudes over the $M_w = 7.4$ (*e.g.*, 1940 event,

with 300 destroyed buildings and around 600 casualties, and 1977 event, with 30 destroyed and other 100 strongly affected buildings and 1400 casualties).

We may say that the necessity appears to define for each site a natural period value range corresponding to strong earthquakes. For example, for INCERC site, in the range of M_w = 7.4–7.7 with assigned PGA values of approximately ~0.2 g to 0.3 g, the recommendation is to avoid designing buildings with natural period range between ~1.2 up to ~1.6 s. 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.

Together, all these studies intend to highlight the specific behaviour of the soil deposits in Bucharest area during strong earthquakes. Starting with the information included herein, consisting in soil deposits analysis performance that could be used as input data for seismic risk mitigation, an important contribution could be brought in a very effective way of getting the right answers to urban site studies. For example, one could decide in fact the site where a new construction should be built or an old one, rehabilitated. These are optional studies, beyond codes, for additional insurance in a seismic region for a more realistic design.

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