Structure Response Analysis of the Seismic Isolated Buildings in Bucharest City

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Abstract. The paper intends to evaluate and analyze the accelerometric data recorded on certain buildings located in the Bucharest metropolitan area, one of the most exposed in Europe, with three strong earthquakes with magnitude $M_W > 7$ in the last century. Starting from information comprised by databases for soils and buildings existing in Bucharest, certain types of structures were selected, according to their specificity (old buildings, retrofitted, etc.) and being continuously seismic monitored. The selected three buildings are equipped with seismic isolators and viscous dampers. The response of these structures, at the ground level, subjected to medium intensity earthquakes will be discussed in terms of peak accelerations and spectral accelerations. Based on the currently accepted standpoint that the dynamic response of certain structures subjected to earthquakes is strongly dependent of the ratio between the natural period of the structure and the dominant period at the construction site, a comparative analysis against free-field data is presented. There would be presented the improvement of seismic response of isolated buildings in Bucharest and the reason these buildings were protected choosing this method. The aim is to provide warnings regarding the severity of seismic events, by means of characteristics of the ground motion, gathered from the response spectra, which may be given soon after the seismic event took place. All the data recorded on instrumented structures during two seismic events ($M_W = 5.5$ and $M_W = 4.8$), together with the subsequent analysis, can represent a reference study for future earthquakes with similar magnitude. The integration of near-real-time seismology with performance-based earthquake engineering allows for providing the information useful for earthquake engineers and decision makers and can enhance the mitigation of seismic risk.

1. Introduction
In Romania, National Institute for Earth Physics through the National Seismic Network (RNS) is monitoring the seismicity of the country that experienced in an interval of 50 years of the last century 4 strong earthquakes: 1940, November 10 with magnitude $M_W = 7.5$; 1977 March 4, with magnitude $M_W = 7.4$; 1986, August 30, with magnitude $M_W = 7.1$; and 1990, May 30 with magnitude $M_W = 6.9$. The first two produced many human victims around 800 (1940) and around 1500 (1977) and economic losses (2 billion $, 1977 value) [1].

The source of all these seismic events is in the Vrancea region, located at approximately 160 km, N-E of Bucharest. After the earthquake of 1977, which had catastrophic effects on high-rise buildings of reinforced concrete built between the two world wars, in Bucharest, has begun a large-scale campaign to calculate the soil layers period of oscillation in various locations of the city. It is generally accepted that the dynamic response of certain structures subjected to earthquakes is influenced by the coincidence...
of the fundamental period of the structure and the dominant period of the site. Starting from information comprised by databases for soils and buildings existing in Bucharest were selected certain types of structures [2-4]. The paper intends to evaluate and analyze the response of three buildings (equipped with seismic isolators and viscous dampers) situated in the Bucharest Metropolitan area, in terms of response spectra.

A case-study is presented, using data from strongest events in the last two years (Table 1): a 5.5 M\text{W} earthquake (October 28th, 2018) and a 4.8 M\text{W} earthquake (January 31st, 2020). Data recorded in free-field and in seismic isolated buildings (3 pairs in total) were analyzed, from the perspective of the earthquake protection system performance.

![Figure 1. Map showing the earthquake epicenters and the location of Bucharest City.](image)

The aim is to quantify the benefits of seismic isolation of the selected buildings in Bucharest, subjected to moderate seismic events that occurred in the Vrancea seismic zone, in terms of response spectra analysis.

| Table 1. List of selected earthquakes. |
|---------------------------------------|
| Date        | Time [UTC] | Depth [km] | M\text{W} |
|-------------|------------|------------|-----------|
| 28-10-2018  | 00:38:11   | 148        | 5.5       |
| 31-01-2020  | 01:26:47   | 118        | 4.8       |

The Bucharest City Hall building (PMB) and Victor Slavescu building (ASE) were constructed at the beginning of XX\text{th} century when no seismic design regulations were in force. For the purpose of this article, the free-field seismic stations were considered at 1.1 km away (BTMR) from the first building and at 600 m (BSTR) from the second have been used as reference (the nearest seismic stations of the
National Seismic Network from the analyzed buildings). Both buildings were equipped with base-isolators and dampers (the first one in 2016 and the second one in 2008). On the ASE building, both sensors are located at the ground level, one is under the seismic isolator, coupled with the ground, and the other one is above the isolator, coupled with the structure. For the Bucharest City Hall, all the sensors are installed on the isolated structure. The third structure is the Arch of Triumph (ARC), a unique structure representing a historic monument - and nearby (180 m) seismic station (ARCB) has been used as the corresponding free-field reference.

For each building and free-field pair, data were analyzed in a comparative manner, as it follows: ARC – ARCB, ASE – BSTR, PMB – BTMR. All three structures were retrofitted (being subjected to the March 4 1977 earthquake) and equipped with seismic isolators and viscous dampers. The performance of this earthquake-protection system was assessed based on earthquake data: ARC, ASE, PMB.

The largest two earthquakes in the last two years have occurred on October 28th, 2018 (MW=5.5) and on January 31st, (MW=4.8), in the Vrancea seismic zone. Both earthquakes were felt in several Romanian cities, including Bucharest, according to the INFP reports [5].

![Figure 2. The selected seismic isolated structures: Victor Slavescu building (left), Bucharest City Hall (center) and The Arch of Triumph (right)](image)

![Figure 3. Example of seismic isolator and viscous damper used for retrofitting](image)

2. Response spectra analysis
One of the services provided by the National Institute for Earth Physics/Magurele is the seismic monitoring of structures (since 2011). The recorded data are transmitted in real time to the National Data Centre. The real-time data acquisition, data exchange and data processing is performed by an automated Antelope seismological system [6] installed at the National Data Center (NDC) of the National Institute for Earth Physics, in Magurele [7].
Figure 4. Examples of recorded acceleration time-histories on the Victor Slavescu building (ASE) for the October 28th, 2018 earthquake (top) and January 31st, 2020 earthquake (bottom)

The input data consist of accelerations, recorded using sensors installed at the ground level (above and under the seismic isolators) of seismic isolated buildings or in free field, depending on the nearest location of the seismic network. An example is provided in Figure 4, for the two analyzed earthquakes. Given the different earthquake magnitude and location, the data reveal higher values for the largest earthquake, as expected. In both cases the values recorded above isolators are smaller than the ones recorded under isolator (coupled with the soil).

Figure 5. Response spectra computed at the base of the Arch of Triumph (above isolator) and free-field (180 m away), for the October 28th, 2018 earthquake (top) and January 31st, 2020 earthquake (bottom)
Qualitative, for the Arch of Triumph structure, where the free-field sensor is close to the location, a clear reduction of the computed response spectra is observed, on both components, with respect to the sensor installed at the base of the isolated structure (Figure 5). The quantitative analysis is presented in the next section, based on maximum values (Table 2).

Figure 6. Response spectra computed at the base of the Victor Slavescu building (under and above isolator) and free-field (600 m away), for the October 28th, 2018 earthquake

Figure 7. Response spectra computed at the base of the Victor Slavescu building (under and above isolator) and free-field (600 m away), for the January 31st, 2020 earthquake

In Figures 6 and 7 are plotted the response spectra computed at the ASE site. The comparison is done using the station installed under the structure, coupled with the ground, with respect to the free-field station and to the sensor located above the isolation system, coupled with the structure. It is clear that
the values of the response spectra are lower, for all the period range and for both earthquakes, when comparing the data recorded on the structure with respect to the data recorded on the ground. However, given the variability of the local soil condition and the distance of 600 m away from the free-field station, one should notice that the values are lower, for both earthquakes and both components, in free-field with respect to the sensor placed under the isolators. The maximum spectral acceleration values ($SA_{\text{max}}$) and the corresponding periods are presented in Table 2 and have been discussed in the next section.

For the Bucharest City Hall the sensor at the base of the structure it is located at the level of the first floor, so right above the isolation system and dampers which are placed at the basement level. The free-field station is located 1.1 km away. Due to this large distance (especially in an urban environment with such large variability in terms of local soil conditions), the direct comparison will not directly indicate the performance of the isolation system, but it can be used as a reference to validate the recorded data. It was highlighted the amplification / reduction of the seismic motion recorded at the ground level (under or above the earthquake protection system) for each structure, in comparison to free-field motion. The data consisted acceleration response spectra of horizontal components on North-South (N-S) and East-West (E-W) direction.

3. Results and discussions
In Table 2 is presented the data recorded by accelerometers during the earthquake, with respect to the free-field data, corresponding to each pair.
The higher values for the maximum spectral accelerations are encountered at basement of the ASE building, where clearly higher values were registered on both horizontal components (394.9 cm/s² and 337.2 cm/s²). Here they drastically overpassed (more than 3 times on E-W component) the corresponding free-field ones (Figure 6).

For the 4.8 Mw earthquake (Jan. 31st 2020), the recorded peak ground accelerations in the Bucharest area have values between 3.3 cm/s² (lowest value, at PMB free-field station, on N-S component) and 13.2 cm/s² (highest value, at ASE station, on E-W component).

The higher values for the maximum spectral accelerations are encountered at basement of the ASE building, where clearly higher values were registered on both horizontal components (32.8 cm/s² and 42.8 cm/s²).

In Table 3 is presented an assessment of the performance of the earthquake protection system, for two structures. These two structures were chosen since the free-field data (or data recorded at the ground level) can be compared with data recorded on the structure. Table 3 presents the percentage of reduction of the maximum recorded values of accelerations and SAmax, on both components and for both earthquakes. The reduction percentage is computed using the free-field data (or data recorded at the ground level, for ASE) as a reference, with respect to the data recorded at the base of the isolated structure, right above the isolators. The two structures were selected given the small distance between the sensors, so the comparison is reliable. The data indicate at least 51% reduction in terms of maximum recorded values of accelerations and at least 45% reduction in terms of maximum spectral accelerations. However, the seismic events are moderate and the actual response of the seismic isolated structures to

Table 2. Engineering parameters (maximum recorded acceleration, maximum spectral acceleration and the corresponding period) for the two earthquakes

| Station Code | Earthquake (Mw) | Sensor location | Component | N-S | E-W |
|--------------|----------------|----------------|-----------|-----|-----|
|              |                |                | Amax (cm/s²) | SAmx (cm/s²) | TAmx (s) | Amax (cm/s²) | SAmx (cm/s²) | TAmx (s) |
| ASE          | 5.5            | Free-field     | 25.5      | 57.3 | 0.29 | 21.5   | 91.7   | 0.15 |
|              |                | Above isolator | 33.4      | 105.0 | 0.16 | 46.5   | 187.6  | 0.16 |
|              |                | Under isolator | 129.4     | 337.2 | 0.14 | 98.6   | 394.9  | 0.15 |
|              | 4.8            | Free-field     | 3.7       | 9.8  | 0.29 | 4.5    | 16.1   | 0.29 |
|              |                | Above isolator | 5.6       | 18.1 | 0.42 | 5.7    | 23.0   | 0.34 |
|              |                | Under isolator | 11.5      | 32.8 | 0.09 | 13.2   | 42.8   | 0.31 |
| ARC          | 5.5            | Free-field     | 53.9      | 122.1 | 0.14 | 42.6   | 114.9  | 0.12 |
|              |                | Above isolator | 17.8      | 48.8 | 0.22 | 9.4    | 30.4   | 0.25 |
|              | 4.8            | Free-field     | 3.5       | 10.9 | 0.22 | 3.8    | 17.7   | 0.29 |
|              |                | Above isolator | 0.8       | 2.6  | 0.26 | 1.2    | 3.8    | 0.14 |
| PMB          | 5.5            | Free-field     | 20.8      | 60.6 | 0.13 | 22.3   | 90.0   | 0.15 |
|              |                | Above isolator | 25.5      | 55.9 | 0.59 | 12.7   | 41.4   | 0.15 |
|              | 4.8            | Free-field     | 3.3       | 10.7 | 0.23 | 5.0    | 21.1   | 0.28 |
|              |                | Above isolator | 3.0       | 10.1 | 0.46 | 4.7    | 17.5   | 0.34 |
strong Vrancea earthquakes, (especially to the large long-period components of the response spectra) is still an open topic.

Table 3. Reduction percentage on the isolated structure for the two earthquakes, on both components, with respect to ground (free-field) data

| Station Code | Earthquake (MW) | Pair | Component | E-W | N-S |
|--------------|----------------|------|-----------|-----|-----|
|              |                |      | A_max (%) | SA_max (%) | A_max (%) | SA_max (%) |
| ASE          | 5.5            | Under – above isolator | 74 | 69 | 53 | 52 |
|              | 4.8            | Under – above isolator | 51 | 45 | 57 | 46 |
| ARC          | 5.5            | Free-field - above isolator | 67 | 60 | 78 | 74 |
|              | 4.8            | Free-field - above isolator | 77 | 76 | 68 | 79 |

A clear diminishing of the SA_max values are observed at the ARC basement structure, comparative to corresponding free-field station (4.5 times lower on E-W component, for the 2018 earthquake). Here the isolation system is placed under the sensor in the basement. The fundamental period values are for the all stations in the range 0.09 s - 0.59 s. Though there are second peaks, especially for the free-field stations (ARC, PMB), none of them overpassed 0.7 s, which mean they are in the short range. The fundamental periods values observed in Bucharest for strong destructive earthquakes are in the long-periods range (>1.0 s), as in the case of the 1977 earthquake, when high spectral accelerations were recorded for periods of around 1.5 s.

These types of analyses contribute to a better understanding of the behavior of the structures when subjected to earthquakes. The seismic monitoring of buildings can give also a rapid damage assessment after a strong seismic event, based on the level of accelerations the buildings experienced, therefore mitigating the seismic risk for densely populated areas in Romania.

This study represented an analysis of data recorded on instrumented buildings and corresponding free-field seismic stations during the last two strongest Vrancea earthquakes in the past 2 years (October 28th, 2018 and January 31st, 2020). Though one of the earthquakes is one of the largest one in the last 20 years and the data collected are very important, both for the research community but also for the engineering community, the peak values have not produced any damages and the selected buildings did not experience any structural damage. The buildings were not chosen by default but considering their specificity. Some of free-field station are deployed in an area where in 1977 earthquake collapsed many reinforced concrete buildings from the pre-World War II period and where more are still in use.

4. Conclusions
The main purpose of this study was to highlight the performance of the earthquake protection systems installed on retrofitted buildings in Bucharest to reduce the lateral forces induced in the structures when subjected to earthquakes.

Some conclusions can be drawn accordingly after analyzing the data in time domain and frequency domain:

• ARC - structure equipped with earthquake protection system (base-isolators and dampers) that has reduced the acceleration recorded at the free-field station by a factor in the range from 3 to 4.5;
• ASE - larger differences of acceleration at base, compared to free-field station located 600 m away (BSTR), with the highest spectral acceleration values. Efficient earthquake protection system, with a reduction of signal with a factor in the range from 2.0 to 3.8;
• PMB - similar or slightly smaller acceleration of the base compared to the one recorded by a free-
field sensor (BTMR) located 1.1 km away. However, due to the distance, the comparison can be only in
a general sense.
• A clear influence of the earthquake-protection systems is highlighted, proving to be a solution for
some older structures subjected to medium earthquakes.

Acknowledgment(s)
This paper was partially carried out within Nucleu Program, supported by MEC, project number
PN19080102.

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