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Post-earthquake warning for Vrancea seismic source based on code spectral acceleration exceedance

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Abstract. Post-earthquake crisis management is a key capability for a country to be able to recover after a major seismic event. Instrumental seismic data transmitted and processed in a very short time can contribute to better management of the emergency and can give insights on the earthquake`s impact on a specific area. Romania is a country with a high seismic hazard, mostly due to the Vrancea intermediate-depth earthquakes. The elastic acceleration response spectrum of a seismic motion provides important information on the level of maximum acceleration the buildings were subjected to. Based on new data analysis and knowledge advancements, the acceleration elastic response spectrum for horizontal ground components recommended by the Romanian seismic codes has been evolving over the last six decades. This study aims to propose a framework for post-earthquake warning based on code spectrum exceedances. A comprehensive background analysis was undertaken using strong motion data from previous earthquakes corroborated with observational damage, to prove the method`s applicability. Moreover, a case-study for two densely populated Romanian cities (Focsani and Bucharest) is presented, using data from a 5.5 M_W earthquake (October 28, 2018) and considering the evolution of the three generations of code-based spectral levels for the two cities. Data recorded in free-field and in buildings were analyzed and has confirmed that no structural damage occurred within the two cities. For future strong seismic events, this tool can provide useful information on the effect of the earthquake on structures in the most exposed areas.

Keywords: post-earthquake warning; design codes; spectral acceleration; Vrancea earthquakes

1. Introduction

The Vrancea region is the most important seismic source in Romania, affecting almost the whole territory of the country. One of the particular characteristics of this seismic source is represented by the NE-SW directivity effects of the earthquakes. Because of this circumstance, the cities that lie outside the Carpathians Arch are exposed to a higher level of seismic risk. For example, the event of March 4, 1977 produced major damage in both directions, affecting large cities such as Iasi, Bucharest, Craiova etc. In this context, it is of great importance to develop and implement modern techniques and tools able to estimate the effect of earthquakes on the built environment in the shortest time possible after a major earthquake. The present study is focused on two cities: Bucharest, the capital of the country, with 2.45 million inhabitants, including the metropolitan area, situated at about 160 km from the Vrancea epicentral area and Focsani, a city close to the epicentral zone, with 124 000 inhabitants.

The comparison of the response spectra at a specific site, with the code spectra in use at the time of occurrence, can provide useful information on the earthquakes effect on different types of buildings. As in the case of the March 4, 1977 earthquake, in Romania, comparing the normalized response spectra of the strong earthquake with the code spectrum (P. 13-70, 1970) in force at the time of occurrence (dotted red line) for the city of Bucharest (INCERC seismic station) reveals that, for buildings with a fundamental period higher than 0.5 seconds (i.e., approximately 5-story high), the spectral accelerations used to compute the design forces were underestimated and the buildings were more prone to damage (see Fig. 1). For this earthquake, it was observed that high-rise buildings (more than 7 stories) were greatly or moderately damaged (Balan *et al.* 1982). Another example of the earthquake absolute acceleration response spectra exceeding the design spectra is the Michoacan earthquake, Mexico, 1985 (Anderson *et al.* 1986), where most of the damage was concentrated in tall buildings, in Mexico City.

Depending on the local soil condition, the response spectra can vary from one region of a country to another (Chopra and Choudhury 2011, Wang *et al.* 2001). The developments and updates of the seismic zonation maps used for design, in terms of peak ground acceleration and shape of the elastic response spectra, are based on seismic hazard studies (Looi *et al*. 2018, Kim *et al*. 2018, Lungu *et*

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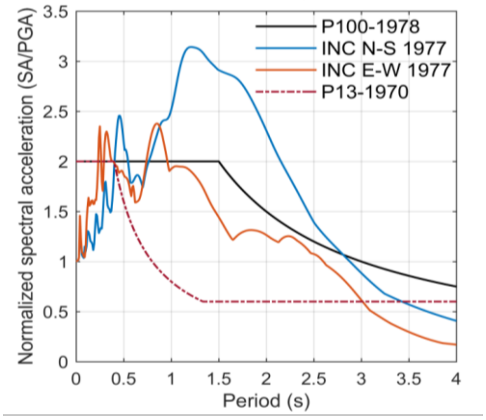


Fig. 1 Normalized response spectra of the 1977 earthquake (INCERC station) and code spectrum for Bucharest, before (red dotted line) and after (black solid line) the 1977 earthquake

al. 2004, Tsang 2018). With the data analyzed from the strong earthquakes (for instance the Romanian 1977 earthquake), the peak ground acceleration for design and/or the seismic zoning map have undergone changes, as it was the case presented in Fig. 1 (P. 100-78 1978). On the other hand, the seismic zoning can be confirmed by the newly recorded data, as Çelebi *et al.* (2018) showed for Mexico City.

The soil condition for the two sites investigated in this paper (Bucharest and Focsani) can be classified according to different criteria. Based on the topographic slope method (Wald and Allen 2007) and on borehole data, Pavel and Vacareanu (2015) assigned the soil class C, according to EN 1998-1 (2004) classification. However, according to the Romanian seismic design code (P 100-1/2013 2013), the soil condition for the two cities is characterized as follows: for Bucharest the corner period T_C=1.6 s and for Focsani T_C=1.0 s. This zonation was based on strong motion data recorded during the large Vrancea intermediate-depth earthquakes that were recorded at both locations. The small value of T_C (0.7 s) corresponds to hard soil condition, while the large value of T_C (1.6 s) corresponds to soft soil conditions (Pavel and Vacareanu 2017).

Nowadays, automatic seismic damage estimation systems (Rapid Response Systems), that take into account both the seismic demand and the vulnerability of the assets, are developed worldwide as a tool to help crisis management following a strong seismic event (Trendafiloski *et al.* 2009, Sesetyan *et al.* 2011, Lang *et al.* 2012, Toma-Danila and Armas 2017).

For nuclear power plants, Reed and Kassawara (1990) proposed a criterion to check if the operating basis earthquake (OBE) has been exceeded after the occurrence of a seismic event. In addition to the cumulative absolute velocity (CAV) parameter, the cited authors compared the response spectrum parameter at minimum 8 frequency points with the OBE earthquake, in the first few hours after the event.

Several other authors have compared the response spectrum of a seismic event to the normative spectrum, for particular cities (Chopra 2012, Dominguezreyes *et al.* 2017, Skolnik *et al.* 2014, Su *et al.* 2006).

The actual design spectrum used in Romania to determine the seismic design forces, for a particular building, is computed by reducing the elastic response spectrum by a behavior factor q, in order to take into account the structure`s capacity to dissipate energy. For the purpose of this article the elastic response spectrum (acceleration elastic response spectrum for horizontal ground component) recommended by the design code will be referred as “code spectrum” and the acceleration elastic response spectrum of a specific earthquake will be referred as the “response spectrum”. This concept of comparing the code-based spectrum to the response spectra of a specific earthquake, minutes after the event and to issue an alarm based on exceedances, can be a very useful tool for the engineering community and for emergency authorities.

The proposed procedure does not consider the properties of the buildings, it is rather a general one, where a specific seismic action is compared to the acceleration level prescribed by the design regulations. The purpose of the procedure is to offer three critical pieces of information, minutes after earthquake: if any code spectra has been overpassed, to what extent and for what periods.

The link with a specific type of building can be assessed through the fundamental period of vibration of the building. The engineers and/or decision-makers can check the level of exceedance for a specific period they are interested in. Empirical relations for the estimation of the building`s fundamental period are given by the design codes and depend on the structural system, material and height of the building. However, these relations do not take into account the ductility, softening, or the accumulated damage during previous events. Moreover, errors can arise due to the fact that during strong seismic events, the fundamental frequency of the building can drop (increase of the fundamental period during earthquake loading) (Clinton *et al*. 2006, Gallipoli *et al*. 2016). The recommendation is to check the exceedance for the initial period and also in the vicinity of that period (especially for larger periods). For a site-specific or building-specific evaluation, a comprehensive structural analysis can be performed using seismic data and the building properties (material, structural system, year of construction, non-linear behavior) in order to evaluate the post-earthquake damage more accurately, but this is beyond the scope of the present work.

This paper compares several code spectra that have been used in Romania and the response spectra of three historical strong seismic motions recorded for earthquakes that occurred in the 20th century and which have affected buildings. Subsequently, an application that uses an automatic algorithm (BRRT 2018) is employed to compare the computed response spectrum for a certain recorded seismic event (M_W=5.5) with several code spectra. This algorithm is able to detect and quantify any exceedance of the code spectra of interest in near real-time and issue an alarm.

2. Post-seismic assessment in Romania

It is very useful to have a “Post Seismic Alarm System” (PSAS) in order to rapidly assess possible damaging effects on the built environment after a strong earthquake. PSAS consists of accelerometers installed on, or near structures, that transmit recorded data to servers to perform quick and reliable automatic analyses. The data can be processed in real-time, online, with a triggering system, or offline (to be effective, the recording and processing durations should be small).

PSAS also provides valuable information that can help authorities to take quick and effective decisions, during the critical and difficult moments immediately following an earthquake. The main benefits that would result from the implementation of PSAS are:

- to enable staff working in the monitored area to take urgent measures to avoid side effects of the earthquake such as fires, chemical leaks etc.;
- to avoid the risk of people working in the monitored areas overreacting; this could avoid unnecessary evacuations or, halting production processes which could be expensive;
- to provide immediate and reliable information on the status of certain structures, including how likely they are to be affected and to what extent, which enables decision makers to better allocate resources and to direct rescue operations.

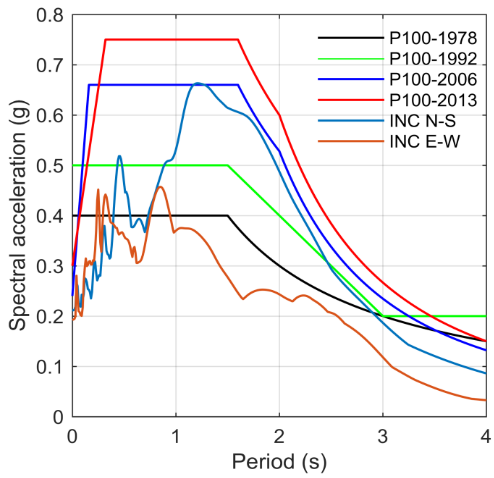
The following buildings of particular importance could benefit from such a system: public buildings (ministries, hospitals, important buildings in the management of post-seismic situations, etc.) industrial, buildings important for business continuity and those that provide basic utilities to the population after a strong earthquake (power stations, industrial buildings with continuous production flow, etc.).

The need for PSAS is also enhanced by the evolution of the design of buildings in the last century, what regulations have been used, since the use of reinforced concrete and multi-story construction in the cities of Romania.

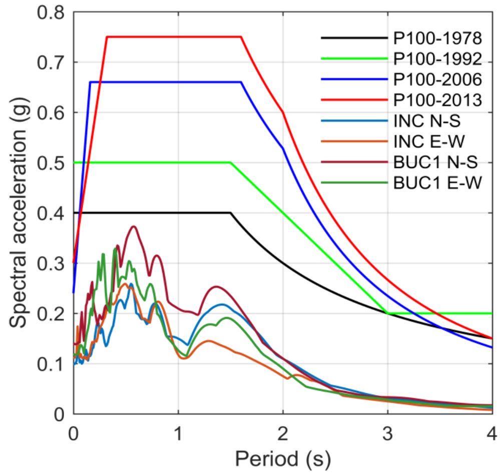
The analysis is applicable to buildings where the date of construction and the seismic code used for design are known. A three-component accelerometer is used, installed on the ground floor or in proximity to the building, so that the measurements can be representative for other buildings in the immediate vicinity. It is considered that there are no significant variations in the geotechnical structure and local geology within a few hundred meters around the recording point. In the case of a medium or strong earthquake, the seismic recordings are sent in real-time to a processing center where the acceleration response spectrum of the earthquake is calculated. Once this spectrum is computed, it is compared with the code spectrum used to design that particular building or for the area.

3. Comparison between the earthquake response spectrum and the spectrum from code

The elastic acceleration spectra of the most important earthquakes of the 20th century in Romania are presented in order to better understand the evolution of the code spectra with respect to the new recorded earthquake data, : March 4, 1977, M_W=7.4; (recorded only at INCERC (INC) station), August 30, 1986, M_W=7.1 and May 30, 1990 M_W=6.9 (ROMPLUS 2019), as they are compared to the code



(a) 1977 earthquake - Bucharest



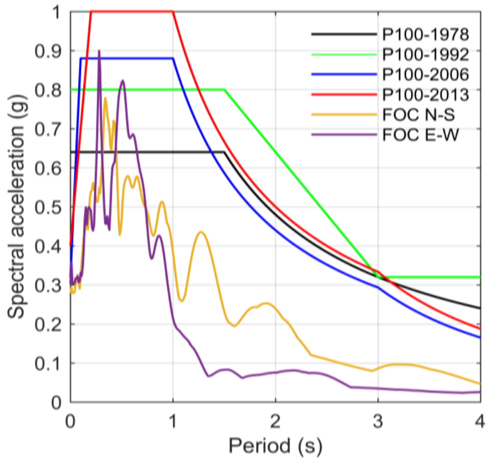
(b) 1986 earthquake - Bucharest

Fig. 2 Response spectra at different stations and evolution of the code spectrum for Bucharest

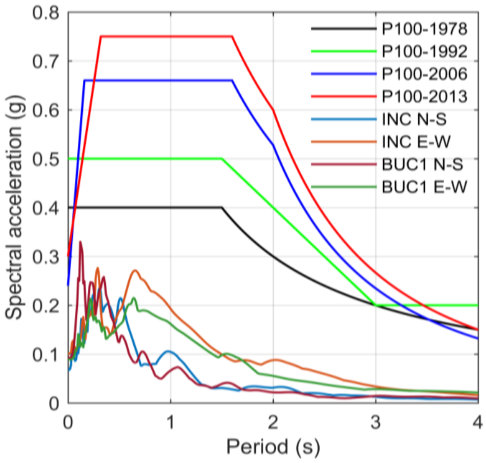
spectra of 1978 (P. 100-78 1978), 1992 (P 100-92 1992), 2006 (P 100-1/2006 2006) and 2013 (P 100-1/2013 2013). For the 1986 earthquake, the analyzed stations were INCERC (INC), Magurele (BUC1) and Focsani (FOC), while for the 1990 earthquake are presented: INCERC (INC) and Magurele (BUC1) seismic stations. The city of Magurele is located in the metropolitan area of Bucharest and its code spectrum is similar to Bucharest city, while the INCERC station is located within the capital. For the purpose of this article, Magurele will be considered part of Bucharest city.

Fig. 2(a) shows the acceleration response spectra of March 4, 1977 earthquake at the INCERC (INC) station (the only available record of this event), on the N-S and E-W directions, compared with the code spectrum (for the city of Bucharest) provided by the design codes of 1978, 1992, 2006 and 2013.

Fig. 2(b) shows the acceleration response spectra of August 30, 1986 for the INCERC site (INC) and the Magurele site (BUC1), on the N-S and E-W directions, compared with the code spectrum (for the city of Bucharest) provided by the design codes of 1978, 1992, 2006 and 2013.



(a) 1986 earthquake - Focsani



(b) 1990 earthquake - Bucharest

Fig. 3 Response spectra at different stations and evolution of the code spectrum for Bucharest city and Focsani city

In the N-S direction, the response spectrum of the 1977 seismic motion (see Fig. 2(a)), significantly exceeds the code spectrum of 1978, mainly for periods higher than 0.5 s, as well as the 1992 code spectrum, mainly for the periods higher than 1 s; is tangent to the P100 - 2006 spectrum (at the corresponding period value over 1 s), but is below the 2013 code spectrum. In the E-W direction, the response spectrum exceeds the 1978 code spectrum and is below the code spectra of 1992, 2006 and 2013. It should be noted that the 1978 code spectrum is exceeded for both components (N-S, E-W). The maximum recorded peak ground acceleration for the 1977 earthquake in Bucharest was 0.2 g and the current value of ground acceleration used for design in P 100-2013 is 0.3 g, while for the previous versions of the codes was 0.2 g (1978 and 1992) and 0.24 g (2006), so a positive evolution is observed.

As can be seen in Fig. 2(b), none of the computed response spectra of the 1986 earthquake at the two stations in the Bucharest area exceeded the code spectra presented in the graph. The existing structures designed according to the code (P 100-1978) should not have experienced structural problems during this seismic event. This was confirmed by the observational damage data after the earthquake.

In Fig. 3(a), the response spectra of the August 30, 1986 earthquake are presented for Focsani city (about 60 km epicentral distance). It was observed that both N-S and E-W components exceed the code spectrum of P 100-78. From this simple graph one should be aware that damage has occurred in the city due to earthquake. Indeed, after a post-seismic inspection in the field, the greater damage (intensity VIII) for the 1986 earthquake was reported in the Focsani-Barlad area (Person 1987). Nowadays, according to the evolution of code spectra for Focsani presented in Fig. 3(a), if a similar seismic event strikes again, the code spectrum could be exceeded for structures designed and built between 1978 and 2006, with a fundamental period ranging between 0.25 s and 0.65 s. The acceleration response spectrum (for a similar seismic motion) is tangent to the code spectrum P 100-2006 and below P 100-2013, therefore the structures constructed after 2006 should be within the safety margin.

In Fig. 3(b) the response spectra of the May 30, 1990 earthquake are shown, for both the INCERC (INC) and the Magurele (BUC1) stations. Even though none of the response spectra intersect the code spectra presented in the graph, some structures from Bucharest-Braila-Brasov area have experienced damage (Person 1991).

4. Recommendations based on code spectrum exceedance levels

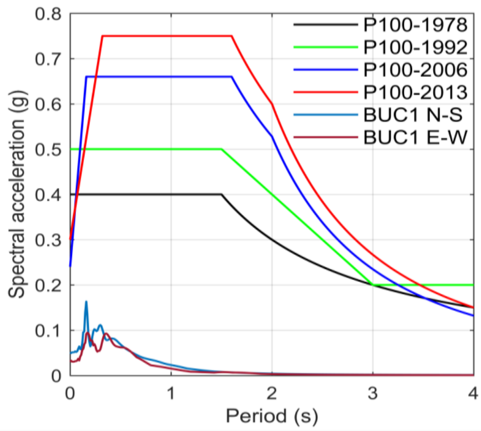
Therefore, when the system works in real-time, the main shock acceleration response spectra are compared with the code spectrum of a building or complex of buildings in the monitored area. As can be seen in the above figures, all three possible situations are encountered in our analysis as follows:

I) The acceleration response spectrum of the recorded seismic motion is below the code spectrum for a specific area. In this situation it is assumed that there are no structural problems with the buildings and there is no need to interrupt their activities or evacuate them.

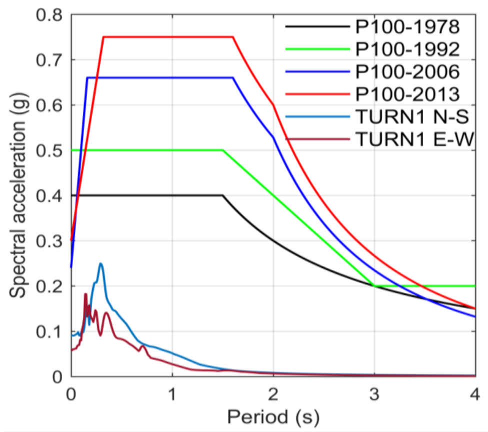
If there is an earthquake above M_W=6.0, however, a structural inspection is required for machinery, equipment, water, gas, electricity or any other existing installation in the buildings, with possible undesirable mechanical effects due to local nonconformities.

II) The maximum value of the response spectrum is almost at the same level, relative to the code spectrum for a specific area. In this case, a cautionary alert should be made and the responsible persons in the monitored area (a building or a complex) have to make a rapid check on the machinery, equipment, water, gas, electricity, or any other existing installation in the building due to the fact that possible mechanical effects could cause malfunctions or minor damages. It is also necessary to inspect the structure (theoretically it should not be affected) cracks that could occur on non-structural walls that do not pose imminent danger.

III) The maximum value of the response spectrum exceeds the code spectrum for a specific area. In this situation, if there is no significant visible immediate damage that requires the application of local measures (pre-established in case of strong earthquakes), a very careful

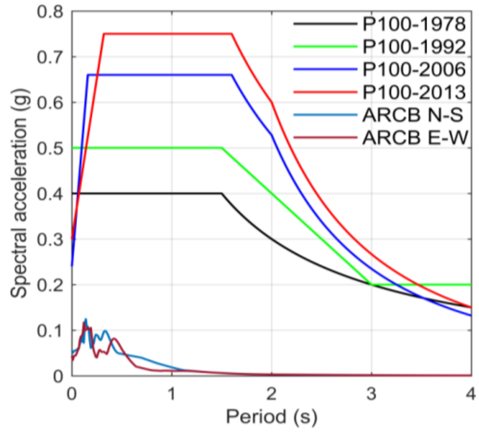


(a) Free-field Magurele seismic station (BUC1)

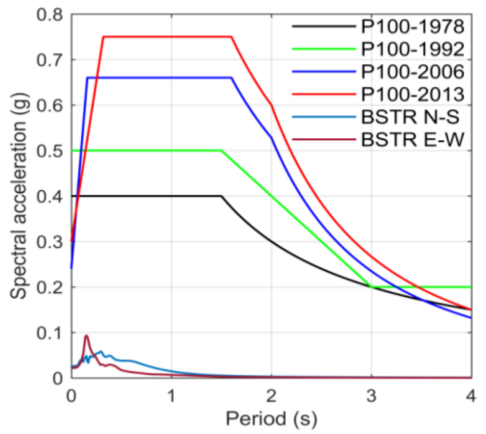


(b) IFA building basement (TURN1)

Fig. 4 Response spectra for the 28th of October 2018 (5.5 M_W) earthquake vs. code spectra



(a) Free-field Arch of Triumph seismic station (ARCB)



(b) Free-field seismic station in Bucharest (BSTR)

Fig. 5 Response spectra for the 28th of October 2018 (5.5 M_W) earthquake vs. code spectra

inspection of the equipment, appliances, water, gas, electricity or any other existing installation in the buildings should be undertaken, because possible mechanical effects could cause dangerous damage to them. It is imperative to have a structural check in the presence of a technical expert in post-earthquake inspections to assess the exact state of the structure or structures in the monitored area, eventual damage to the non-structural elements. Only after the assessment of the structure`s integrity, which should take place in parallel with installation examination, office equipment, furniture, etc. should the normal activity be resumed in the building. The recommendation is that all of these measures should be taken, along with the compliance with the national standards for verification following strong earthquakes, especially in the case of important administrative, socio-cultural and industrial structures, whose operation is critical for emergency management after a strong earthquake.

5. Application on selected Romanian stations and discussion

In order to perform real-time data acquisition, data exchange and data processing, an automated Antelope seismological system (BRRT 2018) is installed at the National Data Center (NDC) of the National Institute for Earth Physics, in Magurele (Neagoe *et al.* 2011).

An extension module of the Antelope package, the Bighorn module, performs real-time computations of spectral acceleration exceedance and issues alarms accordingly (Skolnik *et al.* 2014). The main program is able to continuously compute strong motion response spectra for sets of 3-component waveforms for a large number of stations and then release parameter file spectra packets. These packets are fed to a strong motion response spectra alarm detector, which compares the actual response spectra to a set of exceedance limit spectra and displays them. The post-earthquake alarm is based on the peak values over the entire alarm duration of all observed spectra. The output parameter files may be displayed and archived in a custom database for further processing.

All spectral analysis programs are highly configurable to obtain the best results. At the time of writing this paper the system's real-time performance module is still being tested. This analysis can be run and tested also on previously recorded seismic events. For example, the Bighorn module was used to analyze a recent seismic event of 28.10.2018, local time 03:38:11, lat. 45.60, long. 26.40, depth=148 km, M_W=5.5 for the two highly populated urban areas: Bucharest and Focsani. The intensity on the Mercalli scale was VI in the epicentral zone (National Institute for Earth

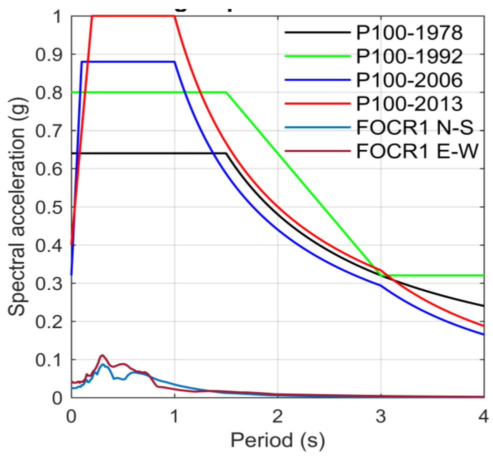


Fig. 6 Response spectra for the 5.5 M_W earthquake recorded at the Unirea Hotel basement (FOCR1) vs. code spectra for Focsani

Physics report).

Although there were no expectations for this event (which was moderate rather than strong) to overpass the code spectra, the authors' intention was to test the method used herein. The main purpose is to highlight that, implementing this procedure for a future much stronger seismic event, would offer useful information about the extent to which some buildings could be affected.

The following figures present the results of this type of analysis for different locations. In Fig. 4: a) Magurele free-field (station BUC1), b) at the basement of a tower type structure situated in Magurele (10 floors high), IFA office building (TURN), of reinforced concrete with shear walls, built in 1974, retrofitted after 1990.

In Fig. 5: a) station ARCB free-field (in the northern part of Bucharest), near the "Arch of Triumph" monument and b) station BSTR, free-field in the central part of the Bucharest, 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.

Fig. 6 shows the acceleration response spectra computed at the basement of Hotel Unirea (FOCR1) from the city of Focsani, near the epicentral zone.

All the recordings were compared to the specific code spectrum recommended by the seismic design codes for Bucharest and Focsani: P 100-1978, P 100-1992, P 100-2006 and P 100-2013.

As can be observed in Figs. 4-6 and Table 1, none of the components of the earthquake in the example even reach the vicinity of the code spectra for this moderate seismic event.

A summary of the results, in terms of PGA values and maximum spectral accelerations ($SA_{\max}$) together with the corresponding period ($T_{\max}$), is presented in Table 1. The PGA values recorded in Bucharest are higher for the N-S direction, whereas for Focsani the maximum PGA recorded is for the E-W direction, possibly due to the directional effects and the position of the two cities with respect to the epicenter. The computed maximum spectral accelerations in Bucharest were in the range of 0.06 g to 0.25 g and correspond to two different period ranges: 0.12 s-0.17 s and

Table 1 Response spectra parameters for selected stations in Bucharest and Focsani

Station	City	Component N-S PGA (g)	N-S SA_{max} (g)	N-S T_{max} (s)	E-W PGA (g)	E-W SA_{max} (g)	E-W T_{max} (s)
TURN1	Bucharest	**0.09**	0.25	0.29	0.06	0.18	0.14
BUC1	Bucharest	**0.05**	0.16	0.16	0.03	0.09	0.17
BSTR	Bucharest	**0.03**	0.06	0.29	0.02	0.09	0.15
ARCB	Bucharest	**0.05**	0.12	0.14	0.04	0.12	0.12
FOCR1	Focsani	0.02	0.09	0.31	**0.04**	0.11	0.3

0.29 s. Peaks were not observed for the long-periods (>1.0 s), as compared to the case of the strong 1977 earthquake, when high spectral accelerations were recorded for periods longer than 1 s. It can be noticed that, for TURN1 and BSTR stations, for the two components (N-S and E-W), the maximum spectral acceleration correspond to different periods (0.29 s and 0.14 s-0.15 s), while for BUC1, ARCB and FOCR1, the periods are consistent for both components (0.16 s-0.17 s, 0.12 s-0.14 s and 0.30 s-0.31 s respectively). Given the magnitude of the case-study earthquake (M_W=5.5) and the depth (148 km), it is not surprising that the values do not indicate any structural integrity problems for the monitored constructed areas, since they all fall far below the code spectra. However, the code spectra could be exceeded by a future strong event.

6. Conclusions

• The seismic response of structures subjected to earthquakes represents the basic concept of seismic design, by assessing the dynamic behavior of certain types of structures and defining engineering parameters that influence building response (acceleration, velocity, spectral acceleration).

• Based on the observations of strong earthquakes in Romania and of the development of design codes in the 20th and 21st centuries, the motivation to implement a "Post Seismic Alarm System" (PSAS) in Romania was highlighted.

• The "Post Seismic Alarm System" (PSAS) is based on comparing and checking the exceedance of the acceleration response spectrum of a recorded seismic event with the code spectrum that was used to design the structure. In doing this one should take into account the large differences between successive editions of design codes used in Romania for the last sixty years.

• The installation of a "Post Seismic Alarm System" (PSAS) is of particular interest for buildings with special functions, which are also required to function after a strong earthquake. The data received is processed and integrated for a quick assessment of the structural situation in a given area.

• Even though the method is simple enough and does not imply complicated calculus and algorithms, one should keep in mind that this procedure can provide, in a very short time, a quantitative indication of the earthquake's effects in a particular area for different building typologies, depending on the construction period.

• The system contributes to the safety of people and business continuity, issuing post-earthquake warnings concerning the degree of danger to which buildings and people could be exposed after a strong seismic event.

• By knowing the exceedance percentage, together with the corresponding period for the exceedance, the approach described herein could provide useful information both for engineers who need to assess the structural state of the buildings and also for emergency planners who can better allocate the available resources minutes after the event.

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