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Dynamic parameters of a RC building extracted from earthquake data using the Random Decrement Technique

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Abstract. The paper presents results from a study on monitoring the long-term variation of the dynamic characteristics of an 11-story reinforced concrete building located near Bucharest. Since the deployment, in December 2013, of a permanent monitoring system, 89 seismic events with a moment-magnitude (M_W) larger than 3.8 were reported. Out of these, 80 were recorded properly by the seismic sensors and the data was used to extract the fundamental frequency and the damping ratio of the building for each event. The main method used to compute the dynamic parameters was the Random Decrement Technique. A dependency of the resulting fundamental frequencies on the maximum accelerations at the base and on top of the building was observed. Due to the structural peculiarities, the fundamental frequency of the building on the transverse direction was lower than the one on the longitudinal direction, this being reflected also by the experimental results. The maximum drop in the fundamental frequency was reported for the M_W=5.5 October 28th, 2018 seismic event. By performing this type of analyses, the dynamic parameters of buildings can be tracked over long periods of time and their variation under seismic excitation can be assessed, allowing rapid detection of structural health alterations.

1. Introduction

Romania is an earthquake-prone country, being shaken by one to six strong seismic events ($M_W > 7.0$) every century [1]. The most recent strong earthquakes that produced large human and economic losses occurred in 1940 and 1977 [2]. However, several smaller-magnitude earthquakes occur rather frequently and, even though they generate less significant damage and losses, their effects on the building stock are important and have to be monitored. The process of monitoring and tracking the integrity of a structure is known as Structural Health Monitoring (SHM).

When subjected to earthquakes, structures respond differently, depending on the input excitation, their dynamic characteristics and the soil-structure interaction.

A direct link between damage and fundamental frequency variation was identified [3, 4, 5]. Thus, this parameter can be used as a straightforward indicator of building damage. Moreover, to obtain reliable information, more complex analyses have to be carried out, as shown in the following sections of the paper.

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The need for structural health monitoring is addressed by various regulations worldwide, including those in Romania. The latest editions of the Romanian seismic code (P100-1/2006 [6] and its revised edition, P100-1/2013 [7]) state the requirement, for all new buildings of importance class I and buildings of importance class II higher than 45 m, located in areas with design accelerations $a_g \ge 0.25g$, to be seismically instrumented with digital accelerometers. However, there is still a lack of harmonized procedures for data management (real-time transmission, processing and interpretation of the results) and more effort should be invested in this strategy before a strong earthquake hits again.

This paper presents an analysis based on earthquake data recorded on a high-rise reinforced concrete shear wall building during nearly 7-year monitoring period (December 2013 to June 2020), aimed to assess the evolution in time of the fundamental frequency of the building and its relationship with the earthquake parameters. The study is a continuation of the work of Tiganescu et al. [8], where ambient vibration data were processed for a particular seismic event (the October 28th, 2018 Vrancea earthquake).

In the current study, data recorded from 80 seismic events were processed in order to extract the fundamental frequency and the damping ratio of the building, using the Random Decrement Technique.

The maximum-magnitude seismic event recorded during the considered period was an $M_W=5.6$ earthquake (in December 2016); the maximum recorded accelerations were recorded during the $M_W=5.5$ October 28th, 2018 event. None of these earthquakes did cause apparent damage to the building. Nevertheless, for stronger seismic events, the effect of nonlinear elasticity is to expect [9], consisting in an instantaneous drop in the frequency value, followed by a recovery. At the same time, a permanent shift in the observed frequency, direct proportional to the damage level of the building is expected to occur.

The continuous data flow for the entire monitoring period can be analyzed in a future study, in order to assess both the changes in frequency due to earthquake excitation and to ambient vibrations.

2. Method and data

The method employed to extract the fundamental frequency of the building and the damping ratio from earthquake data is the Random Decrement Technique (RDT). The method was first used at the beginning of the 1970s to detect failure and measure the damping of aerospace structures [10]. Subsequently, it was used for the dynamic identification of structures (as linear systems) subjected to ambient excitations by Asmussen et al., in 1998 [11], and also in 2005, in the operational modal analysis of civil structures [12].

The building is represented, in a simplified way, by a single degree of freedom (SDOF) system. The solution of the differential equation of motion with respect to time is in the form of an exponentially decreasing sine function depending on the frequency (*f*) and the damping ratio (ξ):

$$h(t) = a_0 e^{-\xi \omega t} \sin(\omega_D t) \tag{1}$$

with:

$$\omega_D = \omega \sqrt{1 - \xi^2} \tag{2}$$

where ω is the angular frequency of the system. The main idea of the method is based on the fact that, for an aleatory input signal, the response of the structure consists of two distinctive parts: a deterministic one (an impulse and/or a step function) and a zero-average aleatory part. By stacking several windows with the same initial conditions, the aleatory part tends to diminish and only the deterministic part of the response remains, i.e.:

$$x(\tau) = \frac{1}{N} \sum_{i=1}^{N} y(t_i + \tau)$$
(3)

where *N* represents the number of windows with the same initial conditions, *y* is the recorded signal of duration τ and t_i is the time corresponding to the initial conditions.

An example of the application of this procedure is presented in Figure 1.

The earthquake data random signature is represented with black line. The signature is exponentially damped, as indicated by the logarithmic decrement [13]. The fundamental frequency (f_0) is computed by averaging the time interval between two successive peaks (T_0):

$$f_0 = \frac{1}{T_0} = \frac{\omega}{2\pi} \sqrt{\frac{k}{m}} \tag{4}$$

where m is the mass of the system and k represents its lateral stiffness.

The damping ratio is estimated by fitting the RDT signal with an exponential decreasing function in the form indicated by Equation 1,

$$\xi = \frac{c}{2\sqrt{km}} \tag{5}$$

in which *c* is the viscous damping of the system.



Figure 1. Example of a Window of Random Decrement Signature: recorded data and fitted exponential decreasing function.

The RDT method can detect small changes in the frequency [14]. The method was successfully applied for the case-study building in Romania, using ambient vibration data [15].

2.1. Seismic events

Between December 2013 and June 2020, 89 earthquakes having a magnitude greater or equal to M_W 3.8 have occurred in Romania (Figure 2). Out of all, 86 occurred in the Vrancea intermediate-depth seismic region, at depths ranging from 65 km to 152 km. A 3.9 seismic event occurred on March 19th, 2020, in the Fagaras-Campulung seismic area, at a depth of 64 km., while two earthquakes were located in the Vrancea crustal area (November 22nd, 2014 and April 24th, 2020).

Date	Time	Depth	Mw	R_{epi}
	(UTC)	(km)		(km)
22-Nov-2014	19:14:17	40.9	5.4	190.4
23-Sep-2016	23:11:20	92	5.5	158.6
27-Dec-2016	23:20:56	96.9	5.6	158.0
28-Oct-2018	00:38:11	147.8	5.5	142.9

Table 1. List of recorded earthquakes with $M_W > 5.0$.

During this period, more than 1500 lower-magnitude seismic events occurred in Romania [16]; the 3.8 moment-magnitude threshold was chosen for a good signal to noise ratio, so that one could separate the recorded seismic signal from the ambient vibrations. Due to some technical issues and the interruption of real-time dataflow for a couple of months (from June to October 2017), only 80 of the

above-mentioned earthquakes were recorded by the seismic monitoring system. The most important events ($M_W > 5.0$) are presented in Table 1, in which R_{epi} is the epicentral distance.



Figure 2. Representation of the earthquake epicenters and their magnitude and depth distribution

All events were felt in Bucharest, but no damage was reported. Data from the first three earthquakes were presented and analyzed in [17], while data from the most recent one (October 28th, 2018) were analyzed in [8, 18].

2.2. Building and instrumentation

The analyzed building represents the headquarters of the Institute of Atomic Physics, IFA (Figure 3), located in Magurele, near Bucharest. The structure of the 11-story office building consists of RC shear walls. Additional and more comprehensive information on the building characteristics and instrumentation are presented in [8] and [15]. The accelerometers are deployed at the basement level and at the 6th and 10th floor, as marked by red ovals in Figure 3.

2.3. Data format

The data consist of three-component (N-S, E-W and vertical) acceleration time-histories, for each of the recorded earthquakes. A pre-event 15 seconds window was extracted. The typical record length is 120 seconds. For the largest-magnitude earthquakes, this time-window was increased. As done in the study of Tiganescu et al. [8], all the records were rotated to match the main axes of the building

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Figure 3. IFA building and schematic representation of sensor location (red ovals).

(longitudinal and transverse). The sample rates of the records are varying from 200 Hz (0.005 s) for the events recorded before October 2016, to 100 Hz (0.01 s) for the events recorded after this date. The raw data were recorded in miniSeed format (Standard for the Exchange of Earthquake Data), and the metadata about stations and channels were archived in dataless format. In order to correct the recordings and to convert them from counts to physical units (cm/s^2), the ObsPy package was used [19]. The subsequent signal processing and the generation of graphics were performed using Matlab [20].

3. Results and discussion

From the acceleration time histories, velocities and displacements were computed, by integration and double integration, respectively.



Figure 4. Recorded acceleration time-histories on top of the building, on longitudinal direction, and computed velocity and displacement time-histories, for the October 28th, 2018 earthquake

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An example of this procedure, for the October 2018 seismic event, is presented in Figure 4 (the recording from the top, on the longitudinal direction). One should keep in mind that these are the maximum recorded accelerations, from all the earthquake dataset (173 cm/s² on L direction and 163 cm/s² on T direction). The maximum computed velocity is 10.3 cm/s and the maximum displacement is 9.8 mm.

A first type of analysis performed was to compare the top maximum accelerations, on both directions, with respect to the maximum accelerations recorded at the base, for each of the 80 recorded events. The results are plotted in Figure 5, on a log-log scale. The diagonal red line represents the limit for which the top acceleration is equal to the base. All the markers represented above the red line indicate that, for all events, the maximum top accelerations exceed the maximum base accelerations, regardless of the earthquake magnitude or distance. This illustrates the generally-observed amplification of the base signal at the upper stories of the building.



Figure 5. Maximum top acceleration versus maximum acceleration recorded at the base of the structure, for both components and for all the 80 seismic events (logarithmic scale). The red diagonal line indicates the equality of the two parameters

For low values of base acceleration (below 0.7 cm/s^2), the dispersion is larger than for base accelerations higher than 0.7 cm/s^2 . The cluster of points indicated by the red circle, that seems to not follow the general trend, corresponds to smallest magnitude earthquakes ($M_W = 3.8$) recorded before October 2016, when the sampling rate was 200 Hz (as detailed in Section 2.3). One possible explanation could be related to the ability of the sensors to capture small variations in the peak amplitude of the signals that are missed by interpolation, when the 100 Hz sampling rate is used. However, for large magnitude events that will induce larger accelerations in the structure, the dispersion is smaller and the maximum accelerations, for both components, follow the general rule.

The evolution in time of the fundamental frequency, computed using the RDT method, is presented in Figure 6, for both directions (longitudinal and transverse).



Figure 6. The evolution in time of the computed fundamental frequency, on both components. The value corresponding to each seismic event is represented by a square mark. The dotted lines capture the evolution from one event to another

A first observation is that the frequency on the transverse direction, for all the seismic events, is smaller than the frequency on the longitudinal direction. This is due to the fact that the elevator shafts (three elevators, two of them grouped in one shaft and an additional elevator in the third shaft) are not disposed at equal distance with respect to the symmetry axes of the building. For most of the events, this difference does not exceed 0.1 Hz. There is a striking exception for the February 22^{nd} , 2018 earthquake, for which the difference reaches 0.2 Hz. This earthquake, a M_w=3.8 event, occurred at a depth of 142 km. For the August 24^{th} , 2014 event, the difference reaches 0.12 Hz, while for the August 30^{th} , 2019 event, 0.13 Hz. As expected, the minimum frequency (for both components) was recorded during the October 28^{th} , 2018 event. On the longitudinal direction, the computed frequency is 1.46 Hz, and for the transverse direction, 1.43 Hz. The second lowest value recorded for the longitudinal direction was for the September 23^{rd} , 2016 earthquake (1.49 Hz) and for the transverse direction 1.44 Hz, in the January 31^{st} , 2020 earthquake.



Figure 7. Fundamental frequency distribution as a function of earthquake magnitude, for both components: longitudinal (blue circles) and transverse (red circles)

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To further investigate the relation between the most representative earthquake parameters, the repartition of the fundamental frequencies with respect to the magnitude of the earthquake, maximum acceleration recorded at the base of the structure and maximum acceleration at the top of the structure will be detailed.

Figure 7 shows the frequency values, for each earthquake, on the L and T direction, with respect to the moment magnitude of the earthquake. There is a trend of a decreasing frequency with the increase of magnitude. It should be noted a lack of data for large magnitude events, with only four seismic events having a magnitude higher than 5.0 (Table 1). On the longitudinal direction, the trend seems to be more pronounced while, for the transverse direction, low values of frequency were obtained for smaller magnitude events (M_W = 4.1, 4.4, 4.6 and 4.8)



Figure 8. Fundamental frequency distribution as a function of maximum recorded top acceleration (top) and base acceleration (bottom), on a logarithmic scale.

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From the distribution of frequency values with the maximum base accelerations and maximum top accelerations (Figure 8), there is a clear linear trend of a smaller computed frequency, with respect to the increase of the maximum accelerations (on a logarithmic scale). For this figure, the dispersion is larger for the longitudinal direction, as compared to the transverse one. One exception is again the February 22nd, 2018 earthquake, for which a frequency of 1.69 Hz was computed, corresponding to a base acceleration of 3.64 cm/s² and a maximum top acceleration of 8.90 cm/s². Normally, a lower frequency value was to be expected, for this range of acceleration values. The highest acceleration values (both at the base level and at the top) were reported for the October 28th, 2018 earthquake and they correspond to the lowest frequency values, as previously mentioned.

The second analyzed parameter was the damping ratio, computed using the random decrement technique. Its evolution over time, during the selected seismic events, is presented in Figure 9.



Figure 9. The evolution in time of the computed damping ratio, on both components. The value corresponding to each seismic event is represented by a square mark. The dotted lines approximate the evolution from one event to another

The values of this parameter fit in the same range on the longitudinal and transverse direction, from 0.8% up to 6%.

4. Conclusion

The presented study was focused on the computation of the dynamic characteristics of an 11-story RC building from recorded earthquake data, in order to assess the influence of various factors on those characteristics.

The response of the building during 80 seismic events, having a magnitude larger than 3.7, was investigated. The dataset consisted in high-quality accelerometric data for which the signal-to-noise ratio allowed the computation of the fundamental frequency during the seismic events, using the Random Decrement Technique.

The maximum accelerations recorded on the top of the building, for both directions, were higher with respect to the maximum accelerations recorded at the base level. A linear trend between the two values is observed, on a log-log scale, with the only outliers from the trend being explained by the modification of the acquisition sampling rate, for small-magnitude events.

The frequency computed on the transverse direction is lower than the one on the longitudinal direction, for all the seismic events. This corresponds to the structural peculiarities of the analyzed building.

A decrease of the frequency values with respect to the increase of all the investigated parameters (moment-magnitude, maximum base acceleration and maximum top acceleration) was observed.

Some exceptions were encountered and further investigations are needed for these particular cases, in order to draw sharper conclusions.

Regarding the damping ratio, a higher variation was noticed; however, the range seems to be constant over the time.

There are a lot of factors that control the dynamic response of buildings to earthquakes, i.e.: the amplitude and frequency content of the input motion, the interactions of structural and non-structural

elements, the concrete micro-cracking and the effect of soil-structure interaction, which is more pronounced for seismic events, as compared to that obtained from ambient vibrations.

For the studied seismic events, no apparent damage (for structural or non-structural elements) was reported during the monitoring period (six years).

The presented approach can represent a starting point for a long-term monitoring strategy to be automatically implemented, both on ambient vibration data [8] and on earthquake data. It is critical that such methodology is fully functional at the time of a future strong earthquake, as it can provide reliable and rapid data-driven information.

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