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# Short-term evolution of dynamic characteristics of a RC building under seismic and ambient vibrations

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Abstract. The post-earthquake evaluation of structural integrity is a critical point to be addressed in case of emergency situations triggered by the occurrence of seismic events. A valuable method that can provide important indices to experts performing this operation is the monitoring of structures with seismic sensors that record how the structure responds to earthquake ground motion. In the case of permanent monitoring systems, reliable information can be obtained by comparing the data recorded before, during and after the earthquake, and checking if any abnormal vibrations of the structure or dynamic parameter changes have occurred. The presented study analysed comparatively, for an 11-story reinforced concrete building, vibration data recorded before, during and after the October 28<sup>th</sup>, 2018 earthquake  $(M_W = 5.5)$ . Continuously recorded data was used to determine the hourly values of the fundamental frequency of the building. The short-term behaviour (72 hours) was assessed, highlighting the modal parameters variation during, before and after the earthquake. In addition, an analysis of the data recorded one and a half hours before the earthquake and one and a half hours after the earthquake provided useful information on the evolution of the building state and on how this "recovered" after the earthquake.

## **1. Introduction**

For a country with moderate to high seismic hazard, Romania, hit by one to six strong Vrancea intermediate-depth earthquakes (moment magnitude  $M_W > 7.0$ ) per century [1], the evaluation and monitoring of the infrastructure condition is critical for the management of emergency situations. The two most destructive strong seismic events in modern times have occurred in 1940 and 1977, the death toll for the last one exceeding 1500 people, out of which more than 1400 in Bucharest [2]. In this context, analysing a building's response to a moderate earthquake can represent a good opportunity to assess its general seismic performance, but can also represent the basis for developing intervention strategies and data-flows in real-time that can be used in the shortest possible time after a strong seismic event. The idea of using the fundamental frequency of the structure as a proxy for its integrity has been applied over the last decades [3-4], but there is still need for the harmonization of procedures in terms of technical equipment, data acquisition, storage, processing and interpretation. In Romania, with the enforcement of the seismic design code P100-1/2006 [5], followed by its revised edition,

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P100-1/2013 [6], all new buildings of importance class I and buildings of importance class II higher than 45 m, located in areas with design acceleration  $a_g \ge 0.25g$ , have to be seismically instrumented with digital accelerometers. However, these are not the most vulnerable in Bucharest; a very important action that should be taken in the near future is to instrument and analyse the data from vulnerable building typologies, especially the middle- and high-rise ones (> 6 stories).

This paper presents an analysis of the data recorded on a high-rise reinforced concrete shear wall building during the most recent moderate earthquake that occurred in Romania (October 28<sup>th</sup>, 2018, moment magnitude  $M_W=5.5$ ), aimed to assess the evolution of the fundamental frequency of the building. The ambient vibration data recorded before, during and after the earthquake was analysed, thus getting an indication if any permanent structural degradation (revealed by the modification of the fundamental frequency) was induced in the structure by the earthquake motion. In addition, since several authors suggested a direct correlation of the variations of the fundamental frequency with atmospheric (environmental) parameter variations, the short-term behaviour (72 hours) of the building response was analysed with respect to the variation of air temperature, relative humidity and wind speed. The variation of these parameters could possibly affect the building's dynamic behaviour, through physical processes that can influence its stiffness or boundary conditions.

#### 2. Method

The method used in the study to extract the fundamental frequency of the building from ambient vibration data and earthquake data is the frequency domain decomposition (FDD). The method was proposed by Brincker et al. (2001) [7] and consists of decomposing the Power Spectral Density (PSD) function matrix by using the Singular Value Decomposition (SVD). It has been shown that this method decomposes the structure response into that of a set of single degree of freedom (SDOF) systems, each corresponding to one individual mode. The relationship between an unknown input x(t) and the measured output/response y(t) can be written as:

$$G_{yy}(j\omega) = H(j\omega)G_{yx}(j\omega)H(j\omega)^{T}$$
<sup>(1)</sup>

where  $G_{xx}(j\omega)$  is the  $(r \ge r)$  PSD matrix of the input, *r* is the number of inputs,  $G_{yy}(j\omega)$  is the  $(m \ge m)$  PSD matrix of the output, with *m* being the number of responses,  $H(j\omega)$  is the  $(m \ge r)$  frequency response function (FRF), the overbar denote the complex conjugate and the *T* denotes the transposed matrix. The FRF can be written as:

$$H(j\omega) = \sum_{k=1}^{n} \frac{R_k}{j\omega - \lambda_k} + \frac{\overline{R_k}}{j\omega - \overline{\lambda_k}}$$
(2)

where *n* is the number of modes,  $\lambda_k$  is the pole and  $R_k$  is the residue:

$$R_k = \phi_k \gamma_k^T \tag{3}$$

At a certain frequency  $\omega$ , only a limited number of modes will contribute significantly (typically one or two modes). If these modes are denoted by  $Sub(\omega)$ , in case of a lightly damped system (i.e. a building), the response spectral density can be written as:

$$G_{yy}(j\omega) = \sum_{k \in Sub(\omega)} \frac{d_k \phi_k \phi_k^T}{j\omega - \lambda_k} + \frac{d_k \phi_k \phi_k^T}{j\omega - \overline{\lambda}_k}$$
(4)

where  $d_k$  is a scalar constant and  $\phi_k$  is the mode shape vector.

The estimate of the output PSD  $G_{yy}(j\omega)$ , known at discrete frequencies, can be diagonalized as:

$$\hat{G}_{yy}(j\omega_i) = U_i S_i U_i^H \tag{5}$$

where the matrix  $U_i = [u_{i1}, u_{i2}, ..., u_{im}]$  is a unitary matrix of singular vectors  $u_{ij}$  and  $S_i$  is a diagonal matrix of scalar singular values  $s_{ij}$ . Near a peak corresponding to the  $k^{\text{th}}$  mode, this mode will be

dominating. If only one mode is dominating, there will be only one term in Equation (4) and the first singular vector  $u_{i1}$  will be an estimate of the mode shape.

$$\hat{\boldsymbol{\phi}} = \boldsymbol{u}_{i1} \tag{6}$$

The method was mainly used for ambient vibration analysis, but is has been proven as robust enough to extract the fundamental frequency of the building also from earthquake data [8-9], by assuming the recorded data as response-only and ignore the fact that the source of vibration is known...

## 2.1. Earthquake

On October  $28^{th}$ , 2018, at 03:38:11 (local time), a 5.5 M<sub>W</sub> (local magnitude 5.8 M<sub>L</sub>) earthquake struck Romania. Its epicentre was located in the Vrancea seismic region (Figure 1) and the focal depth was 148 km, according to the National Institute for Earth Physics (INFP) earthquake catalogue [10]. The maximum intensity in the epicentral area was VI on the MMI scale. The earthquake was felt in Bucharest and recorded on free-field stations within the city and on the five buildings instrumented by INFP.



Figure 1. Earthquake epicentre and major Romanian cities and infrastructures located within 200 km radius from epicentre (INFP report - http://www.infp.ro/doc/eqreports/raport\_cutremur\_28102018\_5.8.pdf\_-last accessed August 2019).

The maximum accelerations at the ground level are given in Table 1 [11].

| Table 1. Maximum accelerations recorded in Bucharest Area for the October 28th 2018 earth | quake. |
|---|--------|
|---|--------|

| Seismic station             | Maximum accel | leration $(cm/s^2)$ |
|-----------------------------|---------------|---------------------|
|                             | E-W           | N-S                 |
| BUC1 (Magurele)             | 29.9          | 49.9                |
| ARCB (near Arch of Triumph) | 44.1          | 53.5                |
| BSTR (Magheru Bulevard)     | 21.1          | 27.6                |

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### 2.2. Building and instrumentation

The case-study building is the headquarters of the Institute of Atomic Physics, IFA (Figure 2), located in Magurele, a city close to Bucharest. Completed in 1974, the 11-story office building has a total height of about 40 m above ground level, the vertical circulation being provided by two elevator shafts. The structure consists of reinforced concrete shear walls. The building was retrofitted twice, first after the  $M_W = 7.4$  earthquake in 1977 and then in the early 90's. This building is representative for a class of low-code high-rise buildings in Romania that suffered damage from the 1977 earthquake, due to a combination of factors pertaining to the knowledge available at the time of their construction.

The instrumentation consists of three digital accelerometers (Metrozet TSA-100S) installed at the basement,  $6^{th}$  floor and  $10^{th}$  floor, as shown in Figure 3.



Figure 2. Institute of Atomic Physics (IFA) Building.



**Figure 3.** Schematic representation of sensor location and label on elevation – IFA building.

The accelerometers were installed in the framework of the National Seismic Network of INFP that is in charge of maintenance and data acquisition.

This building is of particular interest since several other studies have been conducted based on data recorded on this building.

### 2.3. Data

The accelerometric data are recorded in real-time on the structure and sent to the National Data Centre, at the National Institute for Earth Physics. The data are collected in seismic format (MiniSEED - "Standard for the Exchange of Earthquake Data") and the files are organized in one-day (24 hours) files containing accelerations recorded on three directions (North-South, East-West and Vertical) at a sample rate of 0.01 seconds (100 Hz).

For the present paper, data were processed starting with October 27, 2018, 00:00:00 (UTC) until October 29, 2018, 23:59:59 (UTC). For this three-day analysis, the data were split into one-hour files. The pre-processing stage involved data calibration, offset removal and a bandpass pre-filter (0.05 Hz to 45 Hz). All the operations were performed automatically using the ObsPy package [12]. In addition, in order to perform the Fourier analysis, a tapper function was applied on the edges of the signal. Due to this reason, from the twelve five-minute intervals available for processing within each hour, the first

and the last one were removed, being affected by the tapering. Finally, ten intervals of 5 minutes each resulted for every hour, as shown in Figure 4.



**Figure 4.** One-hour data recordings on top sensor (L and T components) starting with 27/10 00:00 and 5 minutes intervals.

Moreover, since the sensor orientation (N and E) were not aligned with the main building axes, the two components were rotated 22 degrees clockwise, to match the building longitudinal and transversal axes (Figure 5). On the other hand, for the analysis of a smaller dataset, from October 27, 2018 23:05 to October 28, 2018 02:05 (1.5 hours before the earthquake and 1.5 hours after the earthquake), a three-hour dataset containing 1080001 samples for each component was analysed. The same pre-processing procedures as for the three-days analysis were carried on for this dataset. Data from all the sensors were available (Figure 6), but for the purpose of this article, an output-only analysis was performed, thus only the data from the top sensor (TURN3) were processed both for the ambient vibration data and for earthquake data.



**Figure 5.** Schematic representation of sensor location and orientation on the plan view– IFA building.

The atmospheric parameters (air temperature, relative humidity and wind speed) were collected every hour, from the meteorological station Bucharest – Filaret, located 10 km away from the analysed building. All the data were provided by the National Meteorological Agency, for all the considered days. Thus, the correlation was tested only on the three-day analysis and not on three-hour analysis.



**Figure 6.** Time-history accelerations recorded on IFA building during the October 28<sup>th</sup> 2018 earthquake.

## 3. Results

One example of the singular value decomposition of the PSD matrix is presented in Figure 7. This example was obtained for a five-minute data interval. In the figure, the red circle indicates the peak value corresponding for the first vibration mode of the structure.

The search grid in the present algorithm was set between 1.0 Hz and 1.8 Hz, since the article deals only with the first vibration mode.



**Figure 7.** Example of SVD and first peak identification for 5 minutes of ambient vibration data recorded starting with 27/10 00:10.

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In other context, the procedure can be applied on superior vibration modes and the search interval can be modified. In addition, by using a higher number of sensors, both the translational and torsional mode shapes of the building can be estimated.

#### *3.1. Three-day analysis*

First, a preliminary analysis was performed by using one-hour datasets and extracting one value of the building's fundamental frequency. The analysis showed very large variations from one sample (hour) to another, variations that reached up to 7 %, which is quite high in the case of ambient vibration data (blue line, Figure 8).



**Figure 8.** Evolution over time of the fundamental frequency of the building, for two cases: blue – one sample every hour, red – mean of 10 samples computed every five minutes (continuous line) and  $\pm$  one standard deviation (dash-dotted line).

To overcome this aspect, a new approach was proposed and the resulting curve revealed a much smoother variation (Figure 8, red line). Because the ambient noise sources and levels of vibrations were not uniformly distributed over the entire recording interval, the new approach computed the value of the fundamental frequency for five-minute time-windows. For every hour, the 10 values of frequency are fitted with a normal distribution and the mean value represents the frequency attributed to that specific interval (Figure 9). Moreover, for a better understanding of uncertainties and intra-interval variations, the standard deviation was also computed.



**Figure 9.** Ten frequency samples (blue) computed from five-minute interval over one hour (27/10 01:00 - 02:00) of data recordings (left) and normal distribution of data (right) mean value and  $\pm$  one standard deviation (red).

The earthquake origin time was 03:38:11 (local time), and the P wave arrival at the base of the structure was 03:38:39, so it took the longitudinal wave 28 seconds to travel from the hypocentre to the studied site. The direct influence of the earthquake motion, in this approach, was captured for the frequency that corresponds to the  $28/10 \ 00:00 - 28/10 \ 01:00$  interval, i.e. the value computed for the first point of the second day of data. From Figure 8, the blue line (one-hour interval time-window

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processing) reveals a 9 % frequency drop (from 1.55 Hz to 1.42 Hz), corresponding to the earthquake occurrence interval, with respect to the value before the earthquake  $(27/10\ 23:00:00\ -\ 28/10\ 23:59:59)$ . The frequency computed immediately after the earthquake  $(28/10\ 01:00:00\ -\ 28/10\ 01:59:59)$  by this approach showed a 10% increase (from 1.42 Hz up to 1.57 Hz). This can indicate that the building has fully recovered the frequency before the earthquake within one hour, but one should keep in mind that this value incorporates also some other variation influencing factors, besides the earthquake effect.

However, just by analysing the data in that interval, without knowing a-priori that it was an earthquake, one can tell with certitude that the building exhibited abnormal behaviour during the time-window where frequency drops, and this cannot be associated only with ambient vibrations.

On the other hand, by using the second approach (where five-minute intervals are processed and the mean value is considered as the fundamental frequency), the frequency drop for the interval when the earthquake occurred is of only 1% (from 1.57 Hz to 1.55 Hz), compared to the previous one. This change, coming after a decreasing trend (the previous value of frequency was 1.58 Hz) will never trigger any alarm or indicate the presence of an earthquake motion. In opposition with the previous approach, the frequency value after the earthquake keeps decreasing (down to 1.54 Hz) and the recovery trend is observed two hours after the earthquake, where the data indicate a frequency value of 1.56 Hz. For this type of analysis, it seems that by computing the mean value for every five-minute interval within one hour, the influence of the earthquake will be "masked" by the other frequency values that are within the normal behaviour limits. This aspect will be discussed in more detail in the following section. The earthquake occurrence is influencing more the standard deviation value, and this could be an indicator in case of a preliminary analysis. The standard deviation of the dataset of the time-window where the seismic event was recorded is 0.067 Hz, which is 2.5 times larger than the average value of the standard deviations computed for the previous day (0.027 Hz).



Figure 10. Evolution of the mean value of the fundamental frequency of the building (red) and atmospheric parameters: air temperature (green), relative humidity (black) and wind speed (blue).

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This can indicate the presence of a low value of frequency within the computed values. A more detailed analysis, as presented in the next section, will give additional information on what the building experienced.

To further check the influence of the atmospheric and environmental conditions on the building's natural frequency, in Figure 10 the mean values of the frequency are plotted, as well as the following parameters: air temperature, relative humidity and wind speed. There were no precipitations during the analysed period. A simple analysis of the plot shows that there is no correlation between the variation of the parameters and the frequency variation. The number of samples is relatively small (73 samples), but still if any daily correlation of the parameters was present it would have been indicated by this graph. The correlation coefficients were computed for each frequency – atmospheric parameter pair. The results are presented in Table 2, according to the formula:

$$p(A,B) = \frac{1}{N-1} \sum_{i=1}^{n} \left( \frac{A_i - \mu_A}{\sigma_A} \right) \left( \frac{B_i - \mu_B}{\sigma_B} \right)$$
(7)

The coefficients can take values between -1 and 1, where -1 represents a direct negative correlation, 1 represents a direct positive correlation and 0 represents no correlation.

As it can be seen from the table, only the temperature presents a direct negative correlation of about 13 %, but this is not enough to draw a clear conclusion.

Table 2. Correlation coefficients of the building's natural frequency with atmospheric parameters.

| Correlation of the frequency | Correlation coefficient |
|------------------------------|-------------------------|
| with:                        |                         |
| Air temperature              | -0.135                  |
| Relative humidity            | -0.057                  |
| Wind speed                   | -0.063                  |
| 1                            |                         |

A study of these variations performed over a longer period (years) would be necessary to draw a conclusion on these correlations.

#### 3.2. Three-hour analysis

For a better understanding of the building's behaviour during the earthquake, a three-hour data interval was analysed separately, centred around the earthquake recording (Figure 11, blue line). The same procedure (FDD) was used to extract the fundamental frequency from the five-minute intervals, except the first and the last interval. It resulted in 34 values of frequency, represented in Figure 11 with orange circle markers. From the plot, the natural wandering of the frequency within minutes, from one interval to another can be observed.



**Figure 11.** Time-history recorded accelerometric data (blue) and the evolution over time of the fundamental frequency of the building, computed from 5-minute intervals (orange circle markers).

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The value corresponding to the earthquake recording is placed at day 28, 00:35 and the data show a sudden 10% drop of the frequency, from 1.56 Hz to 1.42 Hz. The drop is not permanent and, after the earthquake, for the next 15 minutes, the values increase up to 1.57 Hz (1.46 Hz and 1.51 Hz, respectively). This can be an indication that the stiffness of the building has recovered, assuming that its mass remained constant. This hypothesis is supported by the fact that the earthquake has occurred during night-time. One should keep in mind that a drop of 10% in the frequency can indicate a weakening (softening) of the structure of about 19 %, if approximating it by the formula:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \tag{8}$$

Overall, the mean value for the frequencies before the earthquake is 1.57 Hz, while the mean value of the frequency after the earthquake and the subsequent 15-minute recovery is 1.54 Hz, as shown in Figure 11 (red lines). As it can be seen in Figures 8 and 10, the frequency corresponding to October 28, at 06:00 hours, can reach an upper limit of 1.595 Hz, which is close to (practically identical with) the maximum value before the earthquake (1.599 Hz).

#### 4. Discussion

The results are consistent with those obtained by Celebi et al. [13], who found that, for five tall buildings in USA, the first-mode frequencies associated with the low amplitude vibrations (ambient vibrations) are higher than those associated with earthquake data.

Some possible explanations can be related to soil-structure interaction, more pronounced during seismic events than during low-amplitude vibrations, concrete micro-cracking at the foundation or superstructure, interactions of structural and non-structural elements, internal friction. On the other hand, the small variations of the fundamental frequency were reported also in several studies. For instance, Michel and Gueguen [14] found that, under weak motion, these frequency variations of the City Hall of Grenoble may be dominated by variations of the unknown input signal. For other cases of long-term monitoring of building characteristics and atmospheric parameters, correlation between dynamic parameters and degree of soil saturation and air temperature were reported by Herak and Herak [15]. Mikael et al. [16] analysed two stand-alone buildings and concluded that the main parameter controlling these fluctuations is air temperature, with a possible explanation of exposure to the sun that influence the overall stiffness of the building. Clinton et al. [17], for the particular case of the Millikan Library, found correlations of the variation of natural frequency with the heavy rainfalls and strong winds.

#### 5. Conclusion

The purpose of the presented study was to capture and analyse the variation of the fundamental frequency of an 11-story reinforced concrete building from ambient vibration and earthquake data. The method used to extract the fundamental frequency was FDD (frequency domain decomposition); this was applied for a 72-hour continuous signal recorded by the top sensor of the building. As expected, small variations were observed in the ambient vibrations regime. For the forced vibrations (earthquake) a larger variation was observed, up to 10%; followed by the recovery of dynamic characteristics. The study was conducted in an attempt to find correlations of the variation of the fundamental frequency and atmospheric parameters, for the short-term regime (72 hours). The correlation coefficients were computed between the fundamental frequency and atmospheric parameters (air temperature, relative humidity and wind speed) and the first parameter seems to be lightly correlated (13 %). However, a long-term analysis will be necessary to draw a final conclusion. The other two parameters have correlation coefficients of about 6%, very close to 0; this makes it impossible to conclude that they influence in any way the dynamic parameters of the structure.

An additional, more detailed analysis, focused on a three-hour data interval centred on the earthquake occurrence revealed that the frequency values before the earthquake are, on average, 2% larger than those determined after the earthquake. Assuming that the mass of the building remains constant during the analysed interval and that the atmospheric conditions did not cause any permanent

variation of the dynamic parameters, a first conclusion that can be drawn is that the very small variations observed in the overall stiffness could possibly be caused by the earthquake. However, this conclusion can be fully documented only by further studies based on the use of more data, recorded from different moderate earthquakes, as well as from long-term recording of ambient vibrations.

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