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MODAL IDENTIFICATION OF RC BUILDINGS BY AMBIENT RESPONSE TESTING AND ANALYSIS OF THEIR RECORDED RESPONSES TO WEAK EARTHQUAKES

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ABSTRACT

Dynamic identification of the structures of several 6-storey RC residential buildings in the city of Sofia is carried out. Two independent methodologies are applied: (1) processing and analysis of data, recorded during detailed (in a considerable number of measuring points) in-situ dynamic tests of the structures to ambient noise/vibrations, and (2) processing and analysis of the recorded response of one of the buildings to real earthquakes by its permanent seismic instrumentation. The earthquakes are of magnitude $3<M<4$ and depth of hypocenter about -10 km, while the distance from their epicenter to the building site is within 5 km. The identification procedure is focused on the evaluation of the first three natural frequencies of the observed structure. Although these are cases of different type of dynamic input and magnitude, the result obtained by the two methodologies are rather close and differ within 6%. The compiled experimental/observation data and results present an adequate background for further seismic analysis of that type of RC buildings to improve the quality of their design and enhance the earthquake resistance potential of their structures.

Introduction

Dynamic identification of structures through their ambient vibration response processing is carried out after full-scale tests of several 6-storey RC residential buildings in the city of Sofia. The in-situ ambient response of every building is recorded in a considerable number of measuring points by the 12-channel seismic station K2 (Kinemetrics, USA), supplied with uni-axial and tri-axial sensors. The modal identification procedure is fulfilled using independent techniques in the time and the frequency domain. The theoretical background and the signal processing are described in brief followed by the experiment layout and the identified dynamic characteristics derived for

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one of the buildings. Results from the modal identification of this structure (natural frequencies, damping ratios and mode shapes) are demonstrated, incorporating the ARTeMIS (SVS, Denmark) software. The first three natural frequencies, the respective damping ratios and the corresponding mode shapes are accurately estimated and then compared so that the final results are validated. Following these investigations one of these buildings is instrumented with ETNA accelerographs (Kinemetrics, USA) for continuous seismic monitoring.

In 2008 5 earthquakes with M<4 struck the city of Sofia. They were recorded by the stations of the city SGM Network. The earthquake response of the building in question was also recorded by the installed ETNA accelerographs at its basement and at its top. After processing and analysis of the data recorded for the strongest two earthquakes, the respective amplification functions of that structure are computed and natural frequencies are extracted. Then the dynamic characteristics of this structure computed through the two methodologies are discussed and compared. It is concluded that the evaluated parameters extracted by the response of the building to weak earthquakes are in reasonable conformity with the respective results from the detailed in-situ ambient tests.

Modal Identification of RC Buildings by Ambient Response Testing

The dynamic characteristics of the structure of 6-storey RC residential buildings in the city of Sofia (Lozenetz ward) - natural frequencies, damping ratios and mode shapes, are derived from ambient vibration processing. Dynamic identification through ambient vibration processing is a branch of experimental dynamics developing during the last decades due to the availability of highly sensitive sensors with broad dynamic range and the advances in the computer technologies (Cunha 2004). The microtremors of the buildings are recorded by sensors appropriately mounted on the RC slabs. The nodes of the measuring points are carefully selected at the edges of the slabs, near the facades of the buildings, to ensure the recording of the best possible signal and the inclusion of the torsion mode shapes of the structures. This method of modal identification has many advantages compared to the conventional methods of experimental dynamics: (1) relatively easy, fast and cheaper experimentation, without disturbing the exploitation of the building; (2) the use of expensive and clumsy actuators, that might cause damages to the building in the course of the dynamic testing, is eliminated; (3) A number of eigenfrequencies are simultaneously activated by the ambient excitations (gusts of wind, foundation soil microtremors, movement of people around the building etc.)

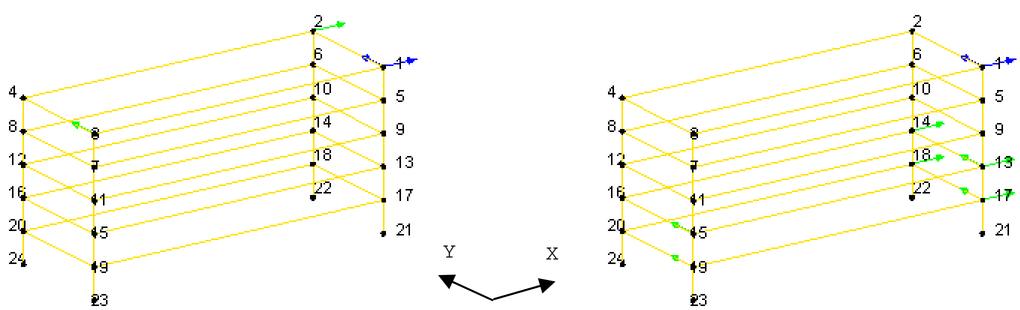
The analysis of the array of microtremor records is carried out by two independent methods for modeling and identification of the dynamic characteristics:

- The Stochastic Subspace Identification (SSI) – in the time domain;
- The Enhanced Frequency Domain Decomposition (EFDD) – in the frequency domain.

The SSI method is applied as basic one in the identification procedure, while the EFDD method is used as complementary for comparison and validation. This is a reasonable approach, since the SSI allows for establishing a tendency for the existence of natural mode at a certain frequency using models with various dimensions. The EFDD is subjective to a certain extent, as the investigator has to select by himself the frequencies corresponding to the local extrema. This is not an easy choice when these are not explicitly outlined in the singular values of the spectral densities.

Experiment Layout

The investigated selected structure is a 6-storey RC (beams, columns and shear walls) residential building (Simeonov and Hadjiyski 2006). Its layout is 29.00 m by 11.50 m. The highest elevation of the roof structures of the building is +20.00 m. A model of 40 DF is used for the visualization of the estimated mode shapes in the dynamic testing and analysis of the structure. The coordinates of the natural mode shapes are computed for those 40 DF. The ambient noise background was measured by tri-axial sensors in free field and at the basement of the structure. The magnitude of the recorded maximum acceleration amplitudes is less than 2.10^{-1} cm/s^2, while the respective power spectrum densities for the interval (0.01 ÷ 1) sec are of order $1.\ 10^{-11}$ g^2/Hz. The microtremors have been measured in the course of 6 recording sessions /6 data sets/. Examples of sensor grouping in a separate session may be seen in Figs.1a, and 1b. One sensor /the reference sensor/ is kept in the same position during all recording sessions in the buildings. The data from this sensor are used to connect the data sets from the different sessions. A tri-axial sensor in node 1 is the reference one for this structure. It is fixed there during all measuring sessions, while all other uni-axial sensors are roved around the building data set for data set. The location of the measuring points is near the ends of the floor slabs to ensure a detailed recording of the structural response. The sensors are mounted at elevations - +28.5 m, +5.70 m , +8.55 m, +11.40 m and +14.25 m. The tri-axial sensor, mounted in node 1 is given in Fig. 2a. The uni-axial sensors mounted in node 13 – in Fig. 2b.



(a) Data set 1 (b) Data set 2

Figure 1. Disposition of sensors by data sets

The code of every sensor is composed of the node number and its direction, e.g. sensor 3Y is the one in node 3 and in the axis Y direction. The Kinemetrics ES-T and ES-U2 type accelerometers with 155dB range, (0÷200) Hz frequency band and ±0.25g amplitude range were used for the measurement. Cables connect them with the recording accelerograph Kinemetrics K-2. The data is recorded at 200 sps and digitized in 24 bit format. The length of the records is 875 s to ensure the proper evaluation of the fundamental natural frequency of the tested structure. The data is decimated and filtered so that frequency components < 25 Hz remain in the signals. The initial processing of data and the following identification of the dynamic characteristics of the building are accomplished by the ARTeMIS Extractor software (SVS, Denmark).

(a) tri-axial sensor in node 1

(b) uni-axial sensors in node 13

Figure 2. Sensors mounted in the investigated building

Modal Identification in the Time Domain (SSI-UPC)

In the SSI techniques a parametric model is fitted directly to the recorded raw time series data returned by the transducers (Van Overschee 1996). The parameters of the model can be adjusted to change the way the model fits to the data – a process often called model calibration. The known time domain modal identification techniques are formulated in a generalized form as innovation state space formulation. The Unweighted Principal Component (UPC) algorithm is utilized for estimation of the parameters of the stochastic state space system, which can also be represented in frequency domain by its transfer function. By a complex transformation of this transfer function using the eigenvectors of the state matrix (physical information) the modal decomposed transfer function is obtained. This representation exposes all the modal parameters - the eigenvalues, the natural frequencies and the damping ratios.

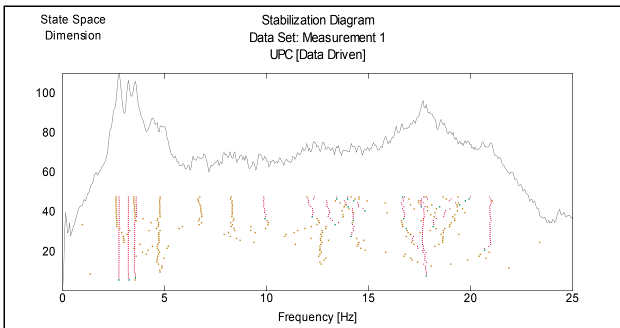


Figure 3. Stabilization diagram for data set 1

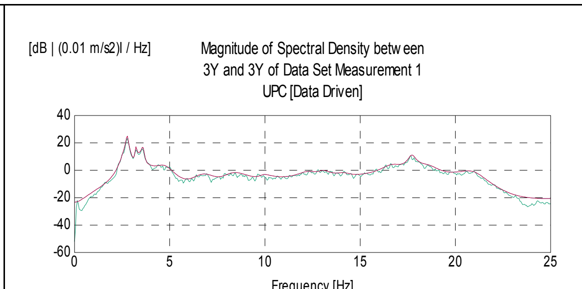


Figure 4. Comparison of the spectral densities for data set 1, sensor 3Y

The natural frequencies and damping, derived by analysis in the time domain, for the structure referred are listed in Tables 1. They are estimated by averaging the relevant frequencies of the optimal models, approximating the data sets. At Fig. 3 is shown a stabilization diagram obtained by approximation of one of the data sets with state space models of different dimensions. The vertical axis lists the dimensions of the available state space models. The vertical lines of red crosses in this figure reveal a repeated trend across the state space models of some of the estimated eigenvalues. If such a repeated trend is located at a resonance frequency it is a strong indication that a structural mode has been estimated. The range of models dimensions have been varied from 10 to 65. For every data set a representative model is selected that approximates it in an optimal way. Then the dynamic characteristics of the optimal models for all the data sets are averaged to identify the final estimates of the stable modes. As an illustration of the quality of approximation achieved in Fig. 4 the curve of the spectral density of the recorded data (in green) is compared to the curve of the selected model for a sensor located in the investigated building.

Modal Identification in the Frequency Domain (EFDD)

In the EFDD local extrema are picked out from the graphs of the singular values spectral densities of recorded microtremors (Brincker 2001). Then a spectral bell is outlined by addition of the values to the left and the right of the selected local extremum (Fig. 5a). The identified spectral bell is then transformed back in the time domain, obtaining a signal that corresponds to a damped vibration of a SDF system (Fig. 5b). The natural frequency is defined by the number of zero crossings, while the respective damping ratio is extracted by an exponential curve fitting the decaying amplitudes of the vibration.

The natural frequencies and damping for the structure, extracted by analysis in the frequency domain are also listed in Tables 1. The natural frequencies are derived as follows: (a) a local maximum is picked out from the graphs of the singular values spectral densities; (b) a spectral bell is outlined by adding the values to the left and the right of the selected maximum; (c) this spectral bell is then transformed in the time domain to obtain the damped vibration trace of a SDF system; (d) the natural frequency and the respective damping are directly computed from this time trace.

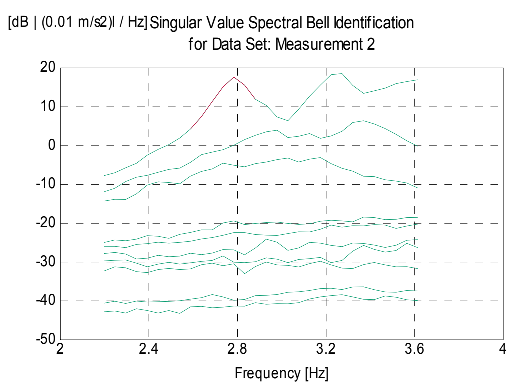


Figure 5a. Spectral bell identification

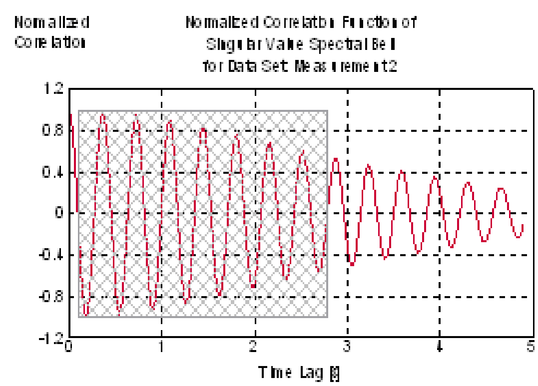


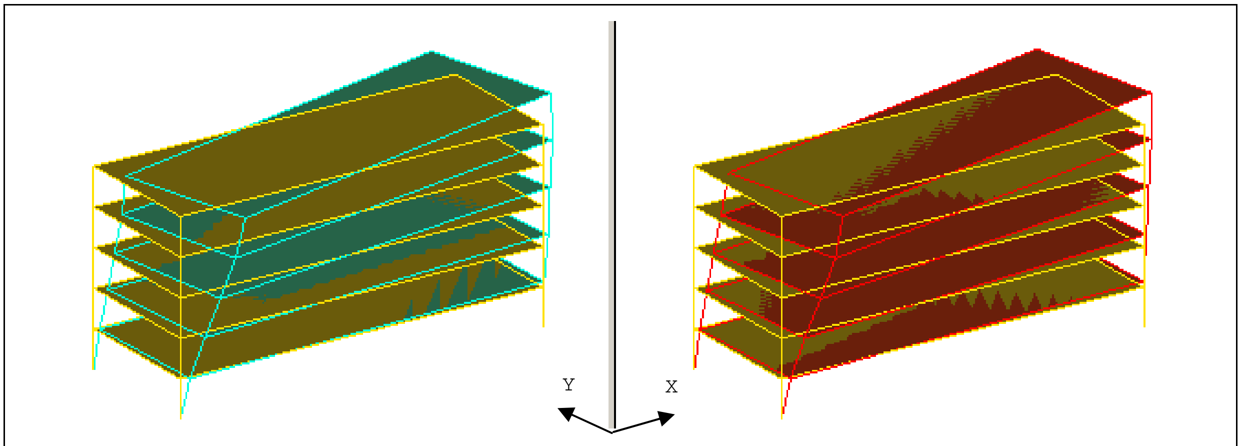
Figure 5b. The corresponding damped vibration of a SDF system

Comparison of the Results Obtained in the Time and in the Frequency Domain

It may be seen in Table 1 that for the structure the differences between the values of the natural frequencies identified by the two methods are minimal (less than 0.6%). Taking account of the good coincidence of the corresponding mode shapes (see Fig. 6), it may be concluded that the identified natural frequencies are consistent. The differences between the damping values derived by the two methods are a little greater but yet less than 1.8%.

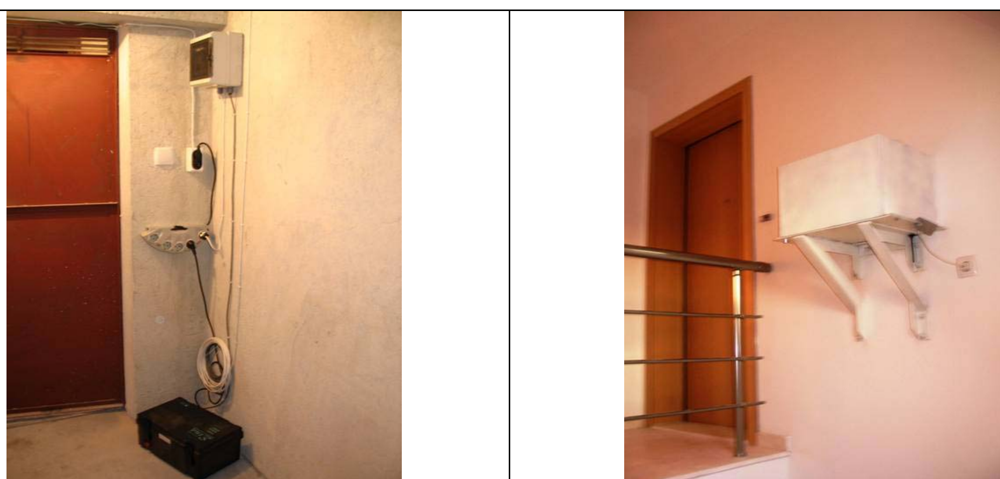
Table 1. Natural frequencies and damping of building # 1, obtained by the SSI and EFDD

№	N.Freq. by SSI (Hz)	Standard deviation (Hz)	N.Freq. by EFDD (Hz)	Standard deviation (Hz)	Diff. (%)	Damp. by SSI (%)	Damp. by EFDD (%)
1	2.781	0.01104	2.778	0.01289	0.10787	1.448	1.426
2	3.224	0.00549	3.242	0.00630	-0.55831	1.405	1.381
3	3.570	0.03222	3.549	0.01892	-0.58824	2.478	2.481



Time domain 3.224 Hz (SSI) | Frequency domain 3.242 Hz (EFDD)

Figure 6. Visualizations of the 2-nd mode shape obtained by the SSI and EFDD methods



SLZ1 - ETNA unit in the basement | SLZ2 - cased ETNA at the 6-th floor level

Figure 7. Permanent seismic instrumentation in RC building

The corresponding graphs of the mode shapes estimated by the two methods are visualized in Fig. 6. The similarity is obvious. This is an ample proof that the modes identified in the time domain are verified in the frequency domain and thus validated.

Following this investigation the residential building was instrumented with ETNA accelerographs (Kinemetrics, USA) for continuous seismic monitoring. Hence, the compiled seismic data to be used for estimation of the dynamic characteristics of the structure from its response to real earthquakes and to juxtaposing them with those obtained through ambient response processing. Photos from the permanent seismic instrumentation of this building can be seen in Fig. 7.

Analysis of the Structure's Response to Weak Earthquakes

5 earthquakes with $2.7<M<4$ of local origin successively attack the city of Sofia in 2008. They were recorded by the stations of the National SGM Network. On 15 November, 2008 Sofia was struck by the strongest earthquake during the last 20 years with a local magnitude M=3.9. Its source was located within the frames of mountain Vitosha fault structure (Glavcheva 2009). Several weaker aftershocks followed (on 16 and 18 of November).

Records of November 15 (EQ#9, Md = 3.7, depth of hypocenter H = 10 km) and November 16 (EQ#10, Md = 3.2, depth of hypocenter H = 10 km) earthquakes are used for the analysis of the instrumented structure's response. The recording points are identified as SLZ1 - in the basement of the building and SLZ2 - at the 6-th floor level respectively. Some basic characteristics of these records are listed in Table 2 (Hadjiyski 2009).

The time domain acceleration traces for the November 15 SLZ1 record may be seen in Fig. 8. Fig. 9 shows the Power Spectral Density of the NS component of that record. It characterizes the distribution of the seismic energy in the frequency domain at the recording point. However, from earthquake engineering point of view the interest is focused in the interval $(0.1 \div 1.0)$ sec. Thus, for the SLZ1 record the principal part of the seismic energy is concentrated in the interval $(0.1 \div 0.7)$ sec, where the natural frequencies of the structure are expected to appear. The magnitude of the PSD for this interval is of order $1.\ 10^{-6}\ g^2/Hz$.

Next the amplification effects within the structure from earthquake inputs (EQ#9 and EQ#10) are analyzed to identify its natural frequencies. The outlined peaks of the amplification function define the triggered natural frequencies of the structure due to the particular EQ event. The structure's Amplification Spectra for EQ#10 inputs in NS and EW direction are given in Fig. 10, and 11 respectively. They are computed as ratios of the corresponding Fourier Amplitude Spectra of the records SLZ2 (top) and SLZ1 (base). In these figures the trace of Fourier Amplitude Spectra for SLZ2 record is designated by a thin line, while the one for SLZ1 record - by a dashed line.

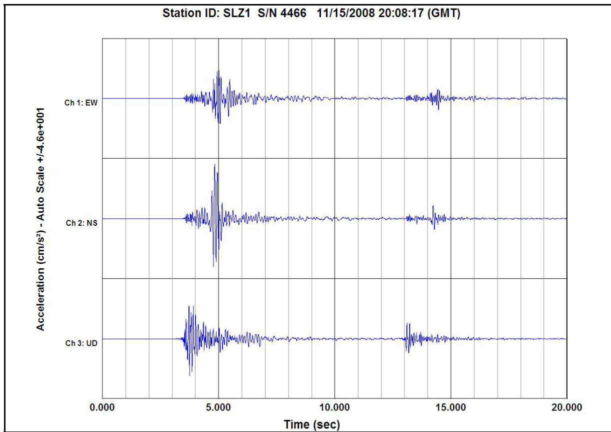


Fig. 8. 3-D accelerogram recorded at SLZ1

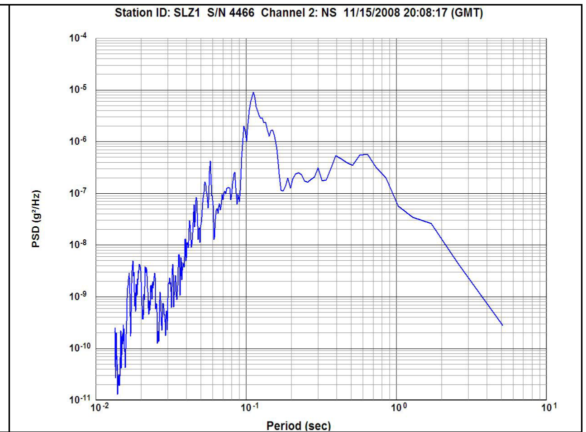


Fig. 9. Power Spectral Density of the EW component of SLZ1 record

Table 2. Characteristics of November 2008 EQ Records (Sofia)

EQ	Station		Epicenter distance	Axis code	Peak Accel.	Peak Sp. Accel.	Predom. Freq.	Order of PSD
#	Code	Cond.	[km]		[cm/s^2]	[cm/s^2]	[Hz]	[g/Hz]
9D	SLZ1	base	3.14	EW NS UD	21.83 42.27 -28.41	203.5	5.4 ÷ 13. 6.2 ÷ 11. 8.8 ÷ 12.	1. 10^{-6}
9E	SLZ2	top	3.14	EW NS UD	-47.04 -92.14 59.78	425.8	2.5 ÷ 2.9 3.3 ÷ 3.7 9.0 ÷ 10.	1. 10^{-5}
10C	SLZ1	base	4.75	EW NS V	8.43 15.76 -32.31	27.2	5.3 ÷ 8.6 5.2 ÷ 9.8 7.0 ÷ 11.	1. 10^{-7}
10D	SLZ2	top	4.75	EW NS UD	21.37 -29.88 60.53	92.6	2.3 ÷ 3.8 3.3 ÷ 4.0 7.2 ÷ 11.	1. 10^{-6}

The identified natural frequencies (periods) of the structure from the full-scale dynamic tests to ambient noise/vibrations (with acceleration amplitudes of less than 2. 10^{-1} cm/s^2 and PSD level of order 1. 10^{-11} g^2/Hz) and its response to real earthquakes (with acceleration amplitudes of less than 5. 10^{1} cm/s^2 and PSD level of order 1. 10^{-6} g^2/Hz) may be seen in Table 3. The maximum observed difference in the values of the identified natural frequencies by the two methodologies is within 6 %.

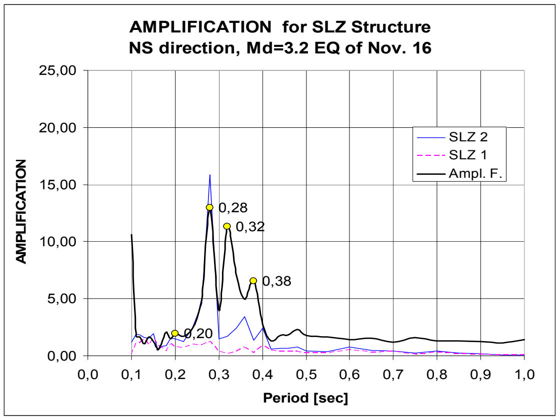


Figure 10. NS Amplification Spectrum

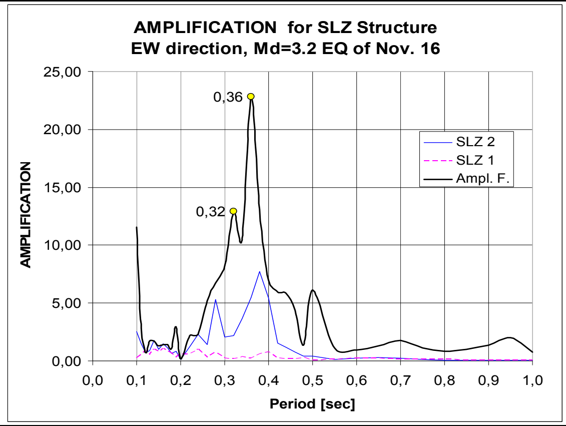


Figure 11. EW Amplification Spectrum

Table 3. Identified Natural Frequencies of the structure

Fn #	From full-scale tests		From EQ#9		From EQ#10	
	Nat. Freq. [Hz]	Nat. Period [sec]	Nat. Period /NS/ [sec]	Nat. Period /EW/ [sec]	Nat. Period /NS/ [sec]	Nat. Period /EW/ [sec]
1	2.78	0.36	0.34	0.38	0.38	0.36
2	3.22	0.31	-	0.32	0.32	0.32
3	3.57	0.28	0.28	-	0.28	-

Conclusions

The natural frequencies of a 6-storey RC residential building were identified by processing and analysis of the acquired data from instrumental observation for two different type of dynamic excitations: (1) ambient noise/vibrations (with acceleration amplitudes of less than 2. 10^{-1} cm/s^2 and PSD level of order 1. 10^{-11} g^2/Hz), and (2) real earthquakes (with acceleration amplitudes of less than 5. 10^{1} cm/s^2 and PSD level of order 1. 10^{-6} g^2/Hz).

The evaluated natural frequencies identified by analysis of the earthquake response of the building structure are in reasonable conformity (within 6%) with the respective results from the detailed in-situ dynamic tests to ambient noise/vibrations. Thus the recorded response of this structure to several weak earthquakes (of different magnitude and epicenter distance to this building's site) verified the validity of the performed detailed full-scale tests of the same building to ambient noise/vibrations.

The applied methodology for dynamic identification of structures by processing the recorded data of their full-scale ambient vibration response proved to be efficient and works well on this type of buildings. The compiled data present an adequate environment for advanced seismic analysis of that type of RC buildings, providing improvement of the quality of their design and enhancing the reliability of their structures.

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