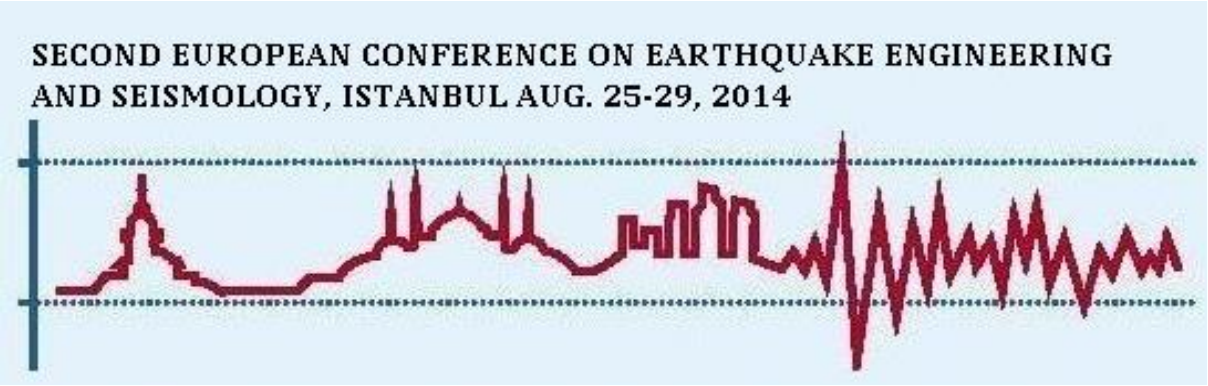

SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

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MODAL IDENTIFICATION OF RC BUILDINGS BY ANALYSIS OF THEIR RECORDED RESPONSES TO WEAK AND MODERATE EARTHQUAKES

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ABSTRACT

Dynamic identification of two types of 6-storey RC residential buildings in the city of Sofia is carried out. For the newly build type of structures, modal identification is performed based on their recorded response to ambient vibrations and weak local earthquakes. For the old type of structures, analysis is made on their recorded response to nearby weak (M ~ 4, H = - 2 km) and distant moderate (M ~ 5.6, H = - 9 km) earthquakes. The identification procedure is focused on the evaluation of the first three natural periods of the investigated/monitored structures. The seismic/dynamic inputs to those structures differ in earthquake source characteristics, energy released, distance to epicentre, seismic waves' travel path etc. Yet, for the first type of structures the maximum observed difference in the values of the identified natural periods is within 6 % and for the second type of structures within 11 %. The accumulated empirical data and the results obtained from analysis present adequate prerequisites for checking the performance and improvement of the earthquake resistance potential of the contemporary buildings, as well as, for the appropriate strengthening and upgrading of existing building stock, targeting seismic risk mitigation.

INTRODUCTION

To acquire empirical data for the seismic action on structures and their dynamic characteristics a number of RC buildings (new and old type) in Sofia city are permanently instrumented with ETNA accelerographs (Kinemetrics, USA) for continuous seismic monitoring. Case study modal analysis of those building structures based on their actual earthquake response to a set of several earthquakes that struck the city lately is presented. Results from dynamic identification of structures through their in-situ ambient vibration response testing and data processing are also submitted.

Selected records of shallow earthquakes that attacked the city of Sofia in 2008, 2010 and 2012 are used in this study. They are of particular interest for the local EQ research/engineering and prevention, because they comprise an essential collection of near field type earthquakes to the accumulated bank of digital records for the building sites of Sofia city.

In 2008 Sofia SGM Network recorded 4 earthquakes with $3<M<3.8$ and epicentres within the territory of the city (Hadjiyski, 2009). The strongest one in the last 20 years with M = 3.7 was on November 15, 2008. Its source was located within the frames of the Vitosha fault structure that is within the southern outskirts of the city. The recorded structural response to that earthquake is used in

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this case study. Four earthquakes with 2.7 < M < 3.6 attacked the city of Sofia in 2010: one on April 27, one on August 27 and two in September - on the 9th and 10th (Hadjiyski, 2011). The most significant one for Sofia in that year (with M = 3.5) took place on September 10, 2010. Its source was located again within the frames of the Vitosha fault structure. The recorded response to that earthquake is also considered hereafter. On May 22, 2012 the strongest Bulgarian earthquake Ms=5.8 (Mw=5.6) occurred in the region of Pernik, following a very long relatively quite period for our territory after the catastrophic 1928. It was generated in the frames of the Pernik-Belchin fault zone, about 20 km SW from the capital Sofia, causing moderate damages in a wide area including the regional town of Pernik (Simeonov et al., 2013) and minor damages in the city of Sofia. The recorded response of buildings in downtown Sofia to that earthquake is further analyzed and assessed too.

The acquired array of records within the city of Sofia in the course of above earthquake events is processed, analyzed and subjected to derivative processing to obtain earthquake engineering relevant characteristics as shown in Table 1. The output results produced are utilized for dynamic identification of two type of RC buildings encoded SLZ (new, seismic resistant) and SGL (old, from 1930-ies). The structural response of every type of RC building is recorded at its basement and at its top. Modal identification is carried out based on the data sets of recorded earthquakes by the installed ETNA accelerographs. The amplification functions obtained as ratio of the Fourier amplitude spectra of the top record to that of the basement record of the structures referred are computed for every set of selected earthquakes. The natural frequencies of the observed structures are extracted through their amplification functions, identified from their specific response to the respective earthquake.

Dynamic identification of SLZ type of RC structures through their ambient vibration response processing is also realized. The in-situ ambient response of the 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. Results from the modal identification of these structures (natural frequencies and damping ratios) applying ARTeMIS (SVS, Denmark) software are submitted. The first three natural frequencies and the respective damping ratios the natural modes are accurately estimated and then compared so that the final results are validated.

ANALYSIS OF SLZ STRUCURE'S RESPONSE TO WEAK EARTHQUAKES AND AMBIENT VIBRATIONS

The investigated SLZ type of structure is a new, modern, seismic resistant 6-storey RC (beams, columns and shear walls) residential building. Its layout is 29.00 m by 11.50 m. The highest elevation of the roof structures of the building is +20.00 m.

Records of November 15, 2008 earthquake (M = 3.7, H = 10 km) and November 16, 2008 earthquake (M = 3.2, H = 10 km) are used for the analysis of the instrumented structure's response. Their sources were located within the frames of the Vitosha fault structure - that is within the southern outskirts of Sofia city. The recording points are identified as SLZ1 - in the basement of the building and SLZ2 - at the 6-th floor level respectively. The earthquake engineering relevant characteristics for SLZ1 November 15, 2008 record is shown in Table 1 (Hadjiyski, 2009).

Table 1. Characteristics of SLZ structural response to M=3.7 Nov. 15, 2008 earthquake

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^2/Hz]
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}
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}

The respective time domain acceleration traces may be seen in Fig. 1. Fig. 2 shows the Power Spectral Density (PSD) 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 ÷ 1.0) sec. Thus, for the NS component of SLZ1 record the principal part of the seismic energy is concentrated in the interval (0.1 ÷ 0.7) sec, where the first natural periods of the structure are expected to appear. The magnitude of the PSD for this interval is of order 1. 10^{-6} g^2/Hz.

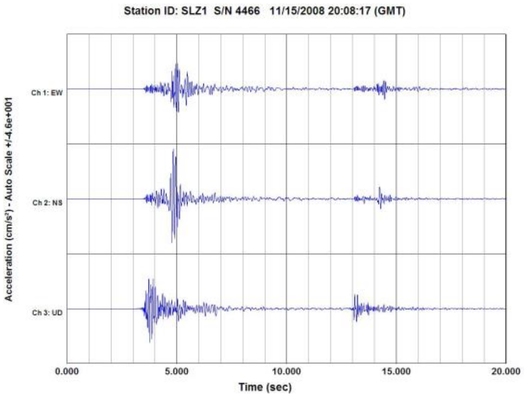

Figure 1. 3-D accelerogram recorded at SLZ1

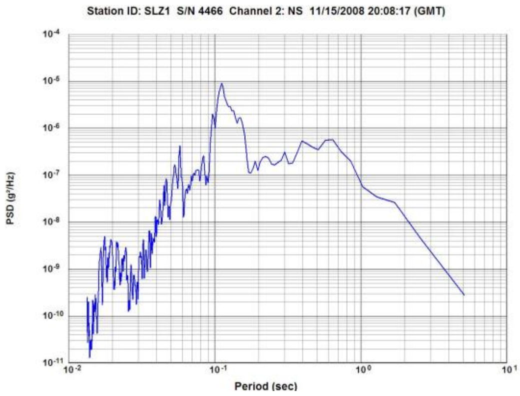

Figure 2. PSD, NS component of SLZ1 record

The earthquake engineering relevant characteristics for SLZ1 November 16, 2008 record is listed in Table 2 (Hadjiyski, 2009). The respective time domain acceleration traces may be seen in Fig. 3. Fig. 4 shows the Power Spectral Density (PSD) of the NS component of that record that characterizes the frequency distribution of the seismic energy at the recording point.

Table 2. Characteristics of SLZ structural response to M=3.2 Nov. 16, 2008 earthquake

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^2/Hz]
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}
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}

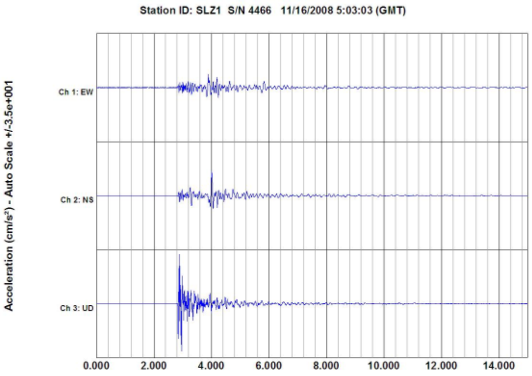

Figure 3. 3-D accelerogram recorded at SLZ1

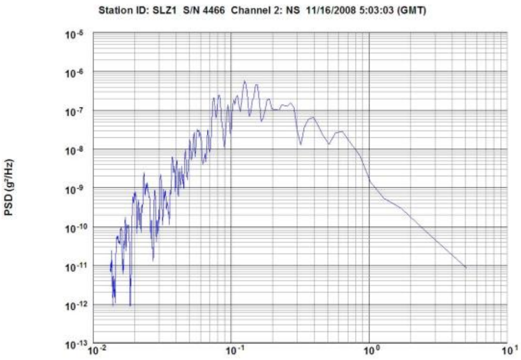

Figure 4. PSD, NS component of SLZ1 record

For this SLZ1 record the principal part of the seismic energy is concentrated in the interval (0.1 ÷ 0.5) sec, where the first natural periods of the structure are expected to appear. The magnitude of the PSD for this interval is of order 1. 10^{-7} g^2/Hz.

Modal identification of the SLZ structure is carried out based on its response to the above set of earthquakes and the data recorded by the installed ETNA accelerographs. The amplification functions for SLZ type of structure are computed for M=3.7 Nov. 15, 2008 quake (Fig. 5 and Fig. 6) and for M=3.2 Nov. 16, 2008 earthquake (Fig. 7 and Fig. 8). Natural frequencies of the observed structure are extracted through their respective amplification functions, identified from its response to those earthquakes /T_1 = (0.34 ÷ 0.38) s; T_2 = 0.32 s; T_3 = 0.28 s/.

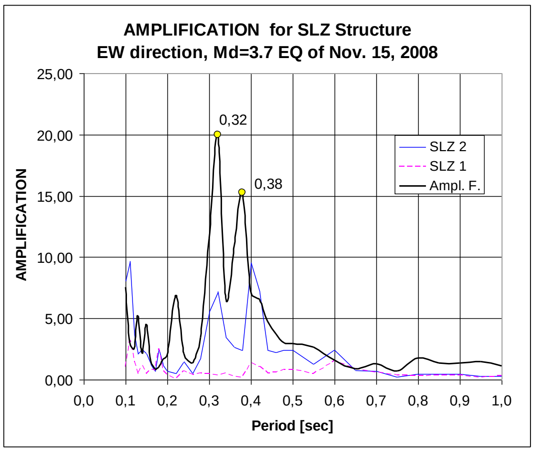

Figure 5. EW Amplification Spectrum

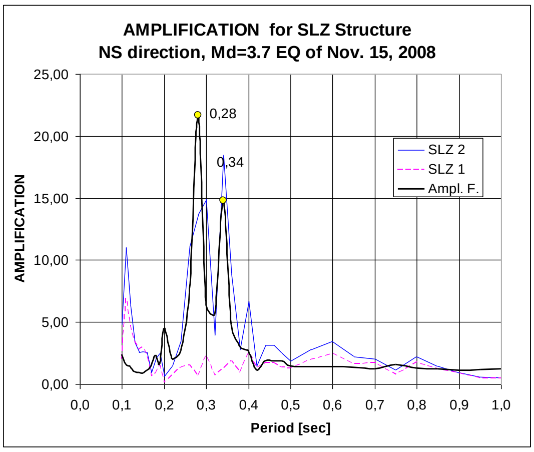

Figure 6. NS Amplification Spectrum

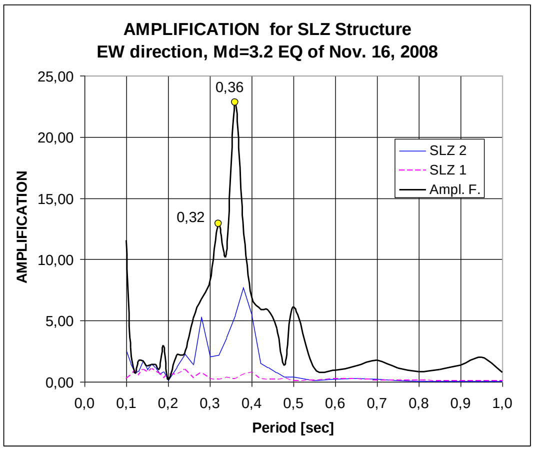

Figure 7. EW Amplification Spectrum

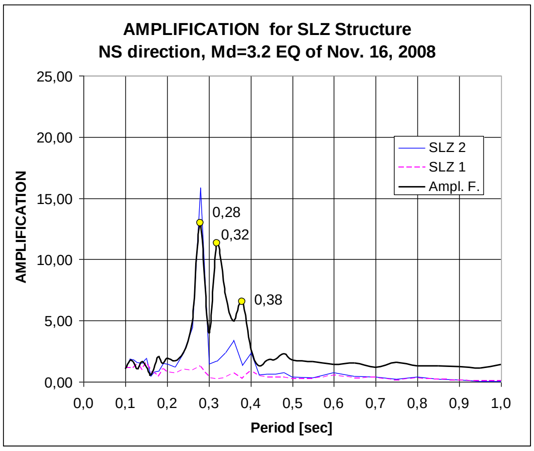

Figure 8. NS Amplification Spectrum

The natural periods of the SLZ structure have been also identified from in-situ dynamic tests for recording the natural response of the structure to ambient noise/vibrations (Cunha et al., 2004). The observational and recording point in SLZ structure during the tests may be seen in Fig. 9. The microtremors of the buildings are recorded by uni-axial and tri-axial sensors appropriately mounted on RC slabs, at all levels of the building, as shown in Fig. 10. The Kinemetrics ES-T and ES-U2 accelerometers with 155dB and (0÷200) Hz frequency band (±0.25g amplitude range) are used for measurement. Cables connect them through junction boxes to the recording Kinemetrics K-2 accelerograph.

The ambient noise background magnitude is 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 8 recording sessions /8 data sets/. The length of each record is more than 900 s to ensure the proper evaluation of the fundamental natural period of the tested structure. The data is filtered so that frequency components < 25 Hz remain in the signals. The accumulated experimental data is processed and consecutively utilized for identification of the dynamic characteristics of the building by the ARTeMIS software (SVS, Denmark).

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 and the Enhanced Frequency Domain Decomposition (EFDD) – in the frequency domain. The SSI method is applied as basic one in the identification procedure. The EFDD method is used as complementary for comparison/validation. A parametric model is fitted directly to the recorded raw time series data returned by the transducers (Overschee et al., 1996). The parameters of the model can be adjusted (calibrated) to change the way the model fits to the data.The SSI allows for establishing a tendency for the existence of natural mode at a certain frequency using models with various dimensions. The Unweighted Principal Component algorithm is utilized for estimation of the parameters of the stochastic state space system. It can be represented in frequency domain by its transfer function. The modal decomposed transfer function is obtained by a complex transformation of this transfer function using the eigenvectors of the state matrix (physical information). This allows for all modal parameters - the eigenvalues, the natural frequencies and the damping ratios to be obtained.

In the EFDD local extrema are picked out and outlined from the graphs of the singular values spectral densities of recorded microtremors. Every identified spectral bell is then transformed back in the time domain, obtaining a signal corresponding to a damped vibration of a SDF system. The number of zero crossings defines the natural frequency. The respective damping ratio is extracted by an exponential curve fitting the decaying amplitudes of vibration (Brincker et al., 2001).

Figure 9. SLZ disposition of observation point

Figure 10. Typical uni-axial sensors disposition

The results obtained (natural periods and damping ratios) for SLZ structure, from its recorded response to ambient vibrations, in the time and in the frequency domain can be seen in Table 3. Differences between the values of natural periods identified by the two methods are minimal (less than 0.61%). The differences between the damping values derived by the two methods are less than 1.75 %.

Table 3. Natural frequencies and damping of SLZ structure, obtained by the SSI and EFDD

№	N. Period by SSI [sec]	Standard deviation [sec]	N. Period by EFDD [sec]	Standard deviation [sec]	Diff. (%)	Damp. by SSI (%)	Damp. by EFDD (%)
1	0.3596	0.00104	0.3599	0.00168	0.08343	1.448	1.426
2	0.3102	0.00549	0.3085	0.00063	0.55105	1.405	1.381
3	0.2801	0.00222	0.2818	0.00179	0.60693	2.478	2.481

Summary of the identified natural periods of SLZ structure from in-situ dynamic response 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 weak 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 4. The maximum observed difference in the values of the identified natural periods by the two methodologies is within 6 %.

Table 4. Identified Natural Periods of SLZ structure

#	From in-situ tests	From M=3.7 Nov. 15, 2008 EQ		From M=3.2 Nov. 16, 2008 EQ	
	Nat. Period [sec]	Nat. Period /EW/ [sec]	Nat. Period /NS/ [sec]	Nat. Period /EW/ [sec]	Nat. Period /NS/ [sec]
1	0.36	0.38	0.34	0.36	0.38
2	0.31	0.32	-	0.32	0.32
3	0.28	-	0.28	-	0.28

ANALYSIS OF SGL STRUCURE’S RESPONSE TO WEAK AND MODERATE EARTHQUAKES

The investigated SGL type of structure is an old 6-storey RC (beams, columns and brick walls) residential building in downtown Sofia, designed in the 1930-ies when there were no seismic codes. Its layout is 23.60 m by 14.20 m. The elevation of the roof slab of the building is +19.20 m.

Records of Sept. 10, 2010 earthquake (M = 3.5, H = 2 km) and May 22, 2012 earthquake (M = 5.6, H = 9 km) are used for the analysis of the SGL instrumented structure’s response. The first quake (weak) was the most significant one for Sofia in 2010. Its source was located within the frames of Vitosha fault structure - within the southern outskirts of Sofia city. The second quake (moderate) was the strongest Bulgarian earthquake during the last 85 years with Ms=5.8 (Mw=5.6) that occurred in the region of Pernik, generated in the frames of the Pernik-Belchin fault zone (20 km SW from Sofia). It caused moderate damages in a wide area including the regional town of Pernik and also some minor damages in the city of Sofia. The recording points are identified as SGL1 - in the basement of the building and SGL2 - at the 6-th floor level respectively.

The earthquake engineering relevant characteristics for SGL Sept. 10, 2010 record is shown in Table 4. The respective time domain acceleration traces may be seen in Fig. 11. Fig. 12 shows the Power Spectral Density (PSD) of the NS component of that record to illustrate frequency distribution of the seismic energy at this recording point. For the SGL1 record the principal part of the seismic energy is concentrated in the interval (0.1 ÷ 0.6) sec, where the natural periods of the structure are expected to appear. The magnitude of the PSD for this interval is of order 1. 10^{-6} g^2/Hz.

Table 4. Characteristics of SGL structural response to M=3.5 Sept. 10, 2010 earthquake

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^2/Hz]
SGL1	base	3.95	EW NS UD	-33.86 -19.22 29.60	94.89 91.80 85.85	3.4 ÷ 4.4 5.6 ÷ 6.4 6.3 ÷ 9.6	1. 10^{-6}
SGL2	top	3.95	EW NS UD	85.56 73.43 65.28	309.18 260.17 250.18	2.2 ÷ 3.2 1.9 ÷ 2.6 6.2 ÷ 9.3	3. 10^{-5}

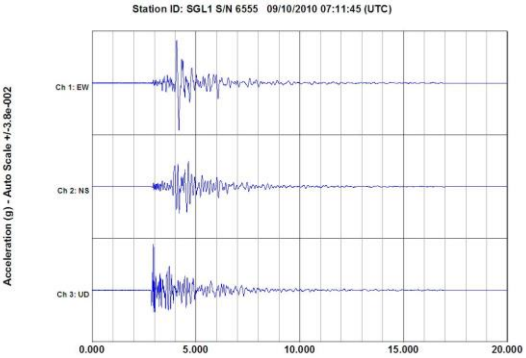

Figure 11. 3-D accelerogram recorded at SGL1

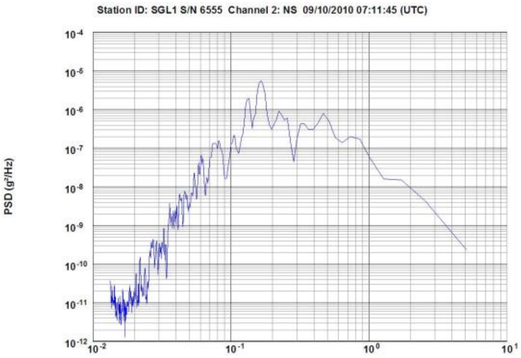

Figure 12. PSD, NS component of SGL1 record

The earthquake engineering relevant characteristics for SGL1 Mw=5.6 (May 22, 2012) record is shown in Table 5. The respective time domain acceleration traces may be seen in Fig. 13. Fig. 14 shows the Power Spectral Density (PSD) of the NS component of that record. For the SGL1 record the principal part of the seismic energy is concentrated in the interval (0.5 ÷ 3.0) sec. The magnitude of the PSD for this interval is of order 5. 10^{-6} g^2/Hz.

Table 5. Characteristics of SGL structural response to Mw=5.6 May. 22, 2012 earthquake

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^2/Hz]
SGL1	base	26.00	EW NS UD	42.62 30.26 21.94	103.56 81.84 66.28	0.5 ÷ 0.8 0.4 ÷ 0.8 0.8 ÷ 1.8	5. 10^{-6}
SGL2	top	26.00	EW NS UD	-99.02 87.15 -46.21	289.52 324.04 215.24	1.7 ÷ 3.0 1.7 ÷ 3.0 1.0 ÷ 10.	6. 10^{-5}

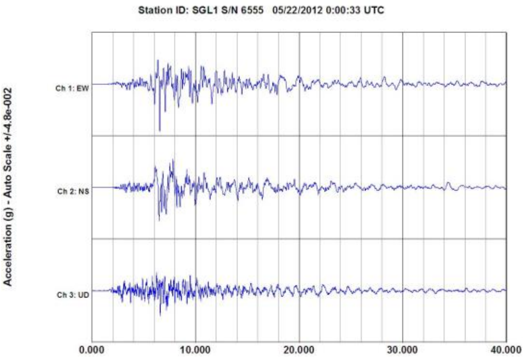

Figure 13. 3-D accelerogram recorded at SGL1

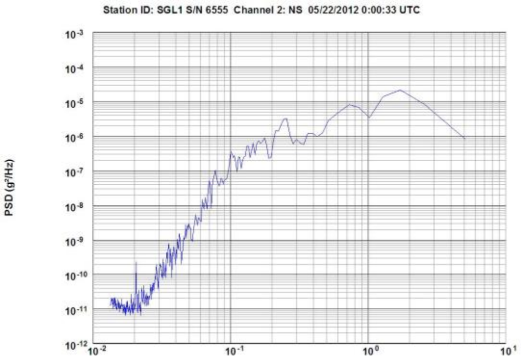

Figure 14. PSD, NS component of SGL1 record

Modal identification of the SGL structure is carried out based on analysis of data recorded by the installed ETNA accelerographs. The amplification functions of SGL structure are computed for M=3.5 Sept. 10, 2010 quake (Fig. 15 and Fig. 16) and for Mw=5.6 May. 22, 2012 earthquake (Fig. 17 and Fig. 18). Natural periods of the monitored SGL type of structure are extracted through its amplification functions, identified from their response to those earthquakes.

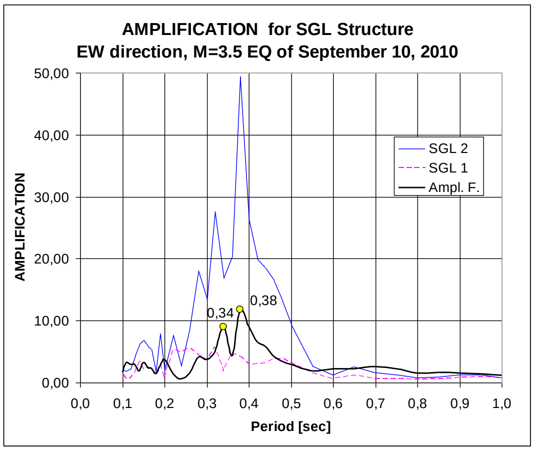

Figure 15. EW Amplification Spectrum

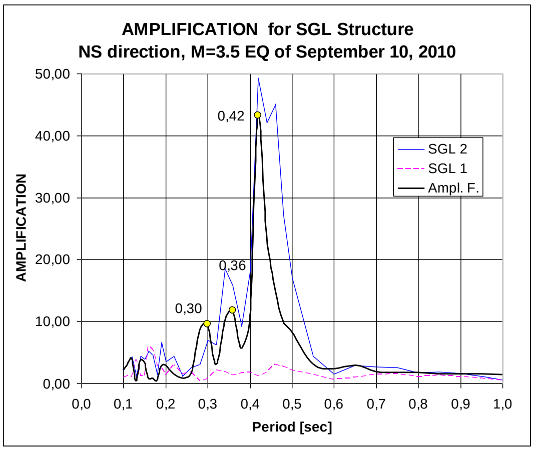

Figure 16. NS Amplification Spectrum

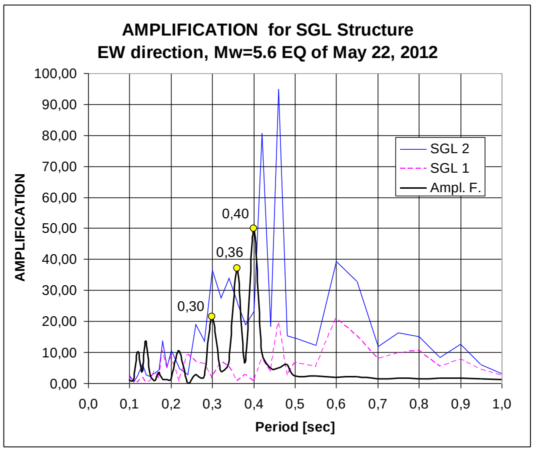

Figure 17. EW Amplification Spectrum

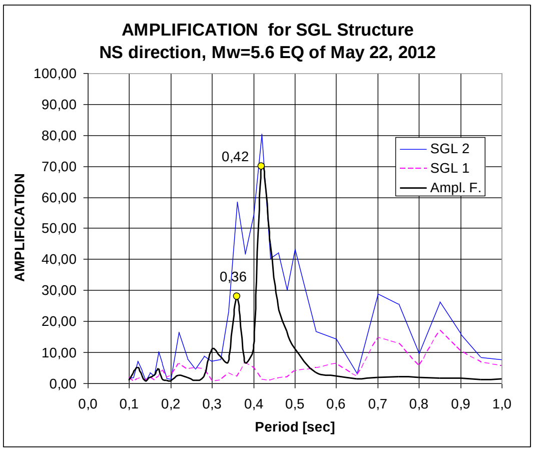

Figure 18. NS Amplification Spectrum

The identified natural periods of the SGL structure from its response to nearby weak earthquake (with acceleration amplitudes of less than 4. 10^1 cm/s^2 and PSD level of order 1. 10^{-6} g^2/Hz) and its response to distant moderate earthquakes (with acceleration amplitudes of less than 5. 10^1 cm/s^2 and PSD level of order 5. 10^{-6} g^2/Hz) may be seen in Table 6. The maximum observed difference in the values of the identified natural periods by the two types of earthquake impacts is within 11 %.

Table 6. Identified Natural Periods of SGL structure

#	From M=3.5 Sept. 10, 2010 EQ		From M=5.6 May 22, 2012 EQ	
	Nat. Period /EW/ [sec]	Nat. Period /NS/ [sec]	Nat. Period /EW/ [sec]	Nat. Period /NS/ [sec]
1	0.38	0.42	0.40	0.42
2	0.34	0.36	0.36	0.36
3	-	0.30	0.30	-

CONCLUSIONS

The natural periods of two types of 6-storey RC residential buildings in the city of Sofia are identified by processing and analysis of the acquired data from recorded experimental measurement and instrumental observation/monitoring for different type of dynamic/seismic 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);
(2) nearby (< 5 km) weak (M ~ 4, H = - 2 km) earthquakes (with acceleration amplitudes of less than 5. 10^1 cm/s^2 and PSD level of order 1. 10^{-6} g^2/Hz);
(3) distant (~ 25 km) moderate (M ~ 5.6, H = - 9 km) earthquakes (with acceleration amplitudes of less than 5. 10^1 cm/s^2 and PSD level of order 5. 10^{-6} g^2/Hz).

Though the seismic/dynamic inputs to the investigated structures differ in: earthquake source characteristics and energy released, distance to epicentre, seismic waves' travel path, regional geology etc., the values of the identified natural periods are within reasonable limits and are practically applicable for earthquake engineering and seismic design purposes.

For the newly build, seismic resistant RC building structures the maximum observed difference in the values of the identified natural periods is within 6 %.

For the old RC building stock the maximum difference in the values of the identified natural periods is within 11 %.

Results produced by this case study provide an adequate environment for performing an advanced seismic analysis of the new type of RC buildings to achieve improvement of the quality of their design. In addition, empirical data is provided to enhance seismic upgrading of the existing building stock thus reducing its structural vulnerability to damaging earthquakes.

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