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DYNAMIC CHARACTERISTICS OF A TALL BUILDING IDENTIFIED FROM EARTHQUAKE AND AMBIENT VIBRATION RECORDS

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Abstract: The paper presents the modal characteristics of a tall building in Bucharest (BRD-SG Tower) identified from earthquake and ambient vibration records. The building was built in the early 2000's and has a reinforced concrete structure (inner shear wall tube and perimeter frames) with 3 underground stories, ground floor and 18 stories. The seismic instrumentation of the building consists of a seismic station with two triaxial acceleration sensors located at the top of the building (+69.6 m) and at the third basement (-9.3 m). The dynamic characteristics of the building are estimated from the seismic records from 23 earthquakes (with moment magnitudes M_W between 3.7 and 6.0) that occurred during the period 2004÷2010. The results obtained from the earthquake records are compared with those obtained from 35 ambient vibration records from the period 2003 ÷ 2010.

Keywords: dynamic characteristics, earthquake records, ambient vibrations

1. Introduction

The modal properties of a structure can be estimated from records of vibrations generated by different sources in the environment [1], [2], [3], [4]. The recorded dynamic response is representative of the measuring conditions. When a permanent seismic instrumentation of the building is available, building seismic records [5], [6] provide information regarding the dynamic behaviour for a wider range of motion amplitudes. In the case of small amplitude ambient vibrations, the structures' behaviour is linear, and its dynamic characteristics are obtained from recorded building response [7].

The results of the vibration records analysis can be considered to monitor the time evolution of the modal parameters of a building, to calibrate numerical models, to identify soil-structure interaction (SSI) effects [8], [9], and for vulnerability assessment [10].

From the analysis of seismic and ambient vibration records it can be determined whether a structure has been damaged following a strong earthquake.

The objective of this study is the modal identification of a tall building (BRD-SG tower, Bucharest, Romania) from seismic motions and ambient vibrations recorded over a long period of time (2004÷2010).

2. Seismic instrumentation of the BRD-SG tower

The National Center for Seismic Risk Reduction (NCSRR, Bucharest, Romania) was created to implement the Japan International Cooperation Agency (JICA) Technical Cooperation Project in Romania entitled „Seismic risk reduction for buildings and structures" (JICA, 2002). In 2003 NCSRR and specialists from OYO Seismic Instrumentation Corp., Japan, installed Kinemetrics (SUA) equipment donated by JICA creating a new digital seismic network in Romania. In 2005-

2006 the NCSRR network was extended with Romanian investment, and other sites were instrumented with Geosig (Switzerland) equipment and technical support [11].

Since 2013 the NCSRR seismic network belongs to the Seismic Risk Assessment Research Center from the Technical University of Civil Engineering Bucharest (UTCB).

In Bucharest two residential buildings of different structural systems located one near the other and two representative public buildings (The National Television Headquarters and the Headquarters of BRD - Société Générale Bank) were instrumented. These buildings were equipped with K2 seismic stations and Episensor FBA ES-T triaxial acceleration sensors from Kinemetrics [11]. In 2006 the main building of the UTCB was instrumented with two IA-1 Geosig stations, placed at the top and at the basement of the building [12].

The Headquarters of BRD – Société Générale, Fig. 1, was designed [13] and erected between 2001 and 2003 and has a dual reinforced concrete structure (inner shear wall tube and perimeter frames), with 3 underground stories, ground floor and 18 stories. At 74 m in height it is one of the tallest buildings in Bucharest. The building is ~26 m (transversal direction) by ~54 m (longitudinal direction) in plan.

The seismic instrumentation of BRD tower consists of a seismic station with two triaxial acceleration sensors, one at the top of the building (+69.6 m) and the other one on the mat foundation (third basement, -9.3 m), Fig. 1. The sensors are located in an almost central position, near the inner shear wall tube, and the top and basement sensors are on the same vertical axis. The sensors horizontal recording axes correspond to the principal directions of the building, transversal direction and longitudinal direction [14].

Fig. 1 – BRD – Société Générale Headquarters, Bucharest

3. Seismic motions recorded at the BRD seismic station

The NCSRR network recorded seismic motions from earthquakes with moment magnitudes ranging between M_W = 3.2 and M_W = 6.0 from Vrancea subcrustal source (focal depths 60÷170 km), Vrancea crustal source, shallow sources from Bulgaria, the Black Sea and North Dobrogea.

Between 2004÷2010, seismic motions from 23 earthquakes were recorded at the BRD seismic station. The characteristics of the recorded earthquakes are presented in Table 1 (source data: National Institute for Earth Physics, Magurele, Romania).

Table 1

Earthquakes recorded at the BRD seismic station

Nr.	Date	Hour UTC+2:00	Coordinates Lat. [°]	Long. [°]	Depth h [km]	Epicentral dist. Δ [km]	Magnitude M_W
1	21/01/2004	05:49:22	45.60	26.40	118	130.3	4.1
2	07/02/2004	11:58:40	45.72	26.64	146	147.9	4.4
3	10/07/2004	00:35:16	45.52	26.49	150	123.3	4.3
4	27/09/2004	09:16:42	45.69	26.32	166	139.2	4.6
5	27/10/2004	20:34:32	45.83	26.77	99	162.7	6.0
6	17/11/2004	11:31:20	45.74	26.72	127	152.0	4.4
7	14/05/2005	01:53:38	45.67	26.47	144	139.1	5.2
8	18/06/2005	15:17:00	45.79	26.91	135	162.6	5.0
9	08/09/2005	16:36:05	45.52	26.37	140	121.1	4.3
10	13/12/2005	12:15:03	45.78	26.79	144	158.0	4.8
11	18/12/2005	15:09:53	45.41	26.04	60	106.8	3.7
12	16/02/2006	02:49:57	45.71	26.66	130	147.3	4.1
13	06/03/2006	10:41:04	45.69	26.53	145	142.3	4.8
14	23/09/2006	05:44:20	45.54	26.40	131	123.8	4.3
15	17/01/2007	13:17:35	45.56	26.41	120	126.1	4.3
16	14/02/2007	06:56:52	45.49	26.52	159	120.7	4.2
17	25/04/2009	17:19:00	45.68	26.62	109	143.2	5.4
18	27/05/2009	03:13:08	45.66	26.50	145	138.5	4.4
19	05/08/2009	07:49:40	43.41	28.76	1	243.8	5.5
20	22/10/2009	12:21:16	45.67	26.54	170	140.4	3.7
21	26/12/2009	23:04:54	45.75	26.72	102	153.0	4.0
22	25/02/2010	15:51:40	45.59	26.55	105	132.0	3.7
23	08/06/2010	15:16:21	45.60	26.41	113	130.5	4.5

Peak accelerations for eight of the earthquakes recorded at the BRD seismic station are presented in Table 2. During the 27/10/2004 earthquake ($M_W = 6.0$), the peak horizontal acceleration at the top of the building was approximately two times higher than at the basement. For all recorded events, the peak horizontal accelerations increase, in average, by about 2.5 times from basement to top.

Table 2

Peak accelerations recorded at BRD-SG building (examples)

Nr.	Earthquake Date	M_W	h [km]	Δ [km]	Sensor	Peak acceleration [cm/s^2] Transv.	Long.	Vert.
1	27/10/2004	6.0	99	162.7	K2 (+69.6 m)	69.4	62.7	36.0
					D (-9.3 m)	36.9	27.1	7.07
2	05/08/2009	5.5	1	243.8	K2	4.60	3.84	2.49
					D	1.42	1.17	0.53
3	25/04/2009	5.4	109	143.2	K2	37.5	25.1	20.7
					D	10.7	13.2	4.02
4	14/05/2005	5.2	144	139.1	K2	14.7	14.1	9.30
					D	3.65	5.06	3.36
5	18/06/2005	5.0	135	162.6	K2	15.7	15.4	8.08
					D	6.03	5.93	2.09
6	08/06/2010	4.5	113	130.5	K2	7.55	5.67	3.45
					D	3.54	3.02	0.98
7	26/12/2009	4.0	102	153.0	K2	3.48	4.84	1.96
					D	1.05	2.07	0.48
8	22/10/2009	3.7	105	132.0	K2	0.85	1.32	0.63
					D	0.29	0.59	0.12

The variation of the peak accelerations recorded at the top of the building (+69.6 m) with earthquake magnitude and epicentral distance is presented in Fig. 2.

The trend of increasing peak accelerations at the top of the building with increasing magnitude can be seen from Fig. 2. An exception appears in the case of the 05/08/2009 earthquake that had its hypocenter in the Black Sea. Because of the large epicentral distance and small focal depth, small peak accelerations were recorded during this earthquake (Table 2), even though it had a magnitude of $M_W = 5.5$.

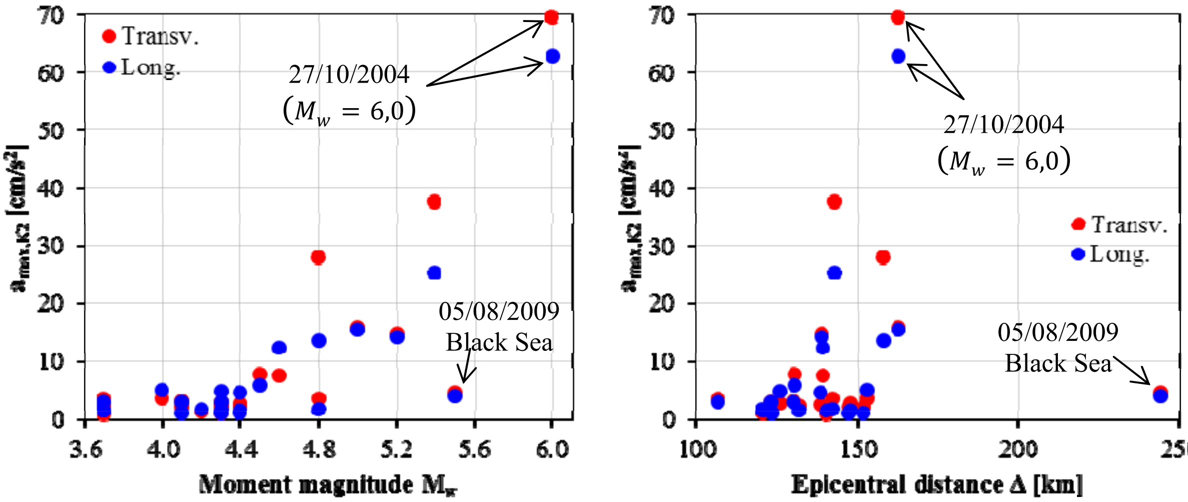

Fig. 2 – Variation of the peak accelerations recorded at the top of the BRD-SG building with earthquake magnitude and epicentral distance

4. BRD building seismic records analysis

The horizontal accelerations at the basement and top of the building recorded at the 27/10/2004 subcrustal Vrancea earthquake ($M_W = 6.0$) are presented in Fig. 3.

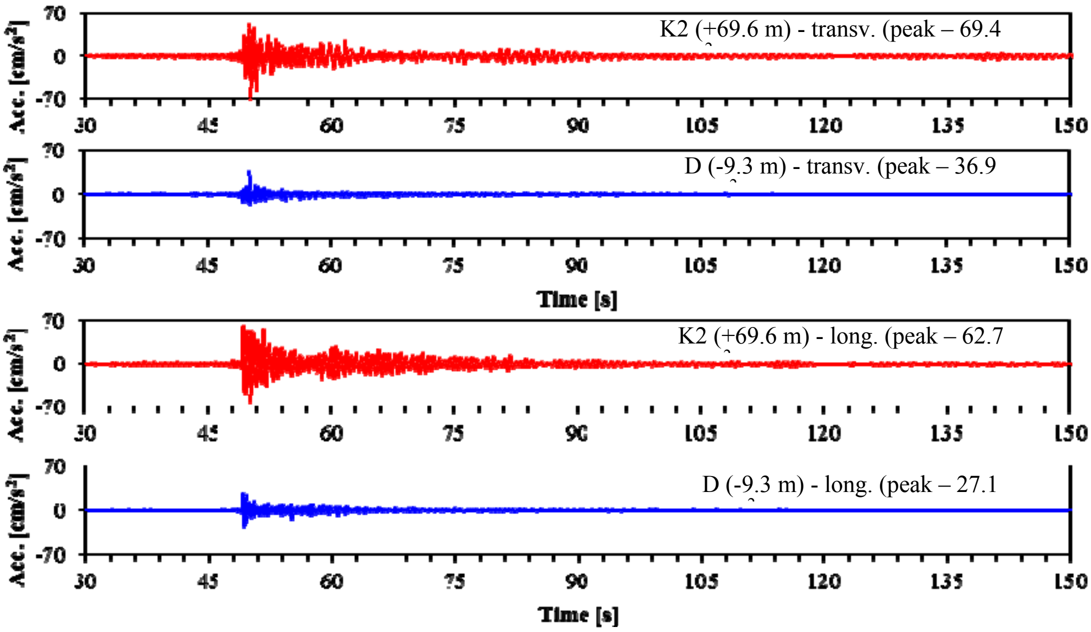

Fig. 3 – Horizontal acceleration records at top and basement of BRD building (27/10/2004 subcrustal Vrancea earthquake, $M_W = 6.0$)

The horizontal accelerations at the basement and top of the building recorded during the 05/08/2009 crustal Black Sea earthquake (M_W = 5.5) are presented in Fig. 4.

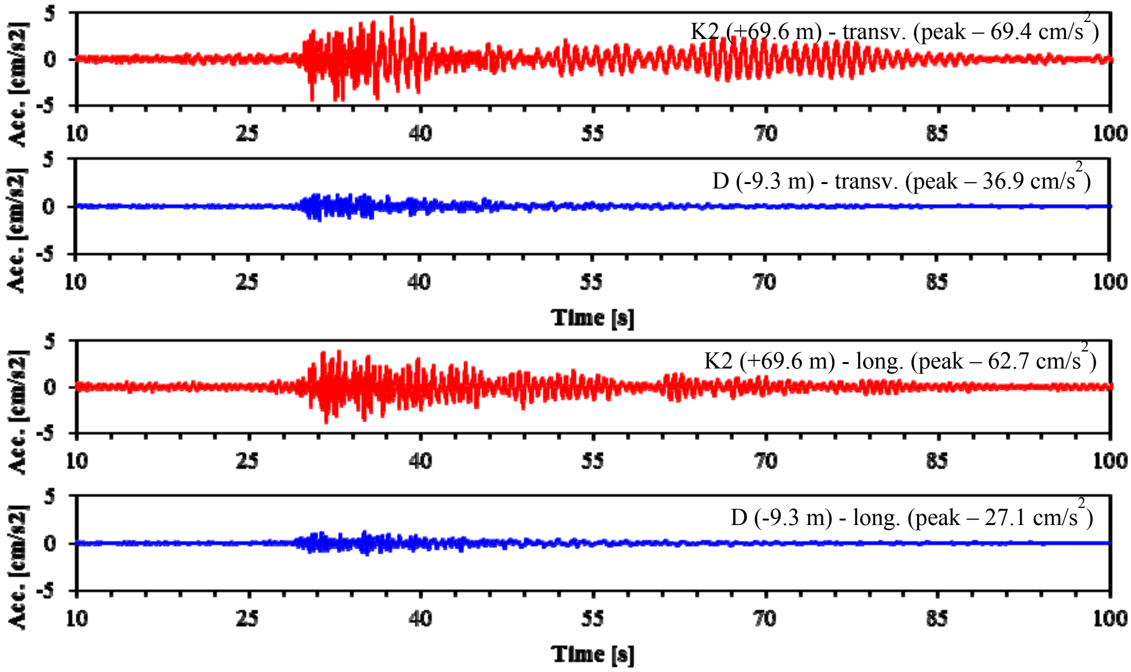

Fig. Error! No text of specified style in document. – Horizontal acceleration records at top and basement of BRD building

(05/08/2009 crustal Black Sea earthquake, M_W = 5.5)

The modal frequencies of the BRD building were identified from the spectral analysis of the motions recorded during the earthquakes in Table 1 [15].

The modal frequencies of the building were estimated from spectral representations: Fourier amplitude spectra (FAS) and power spectral densities (PSD) of top motions, top over basement spectral ratios. The Fourier amplitude spectra of the top motions (+69.6 m) recorded during the 27/10/2004 and 05/08/2009 earthquakes are presented in Fig. 5.

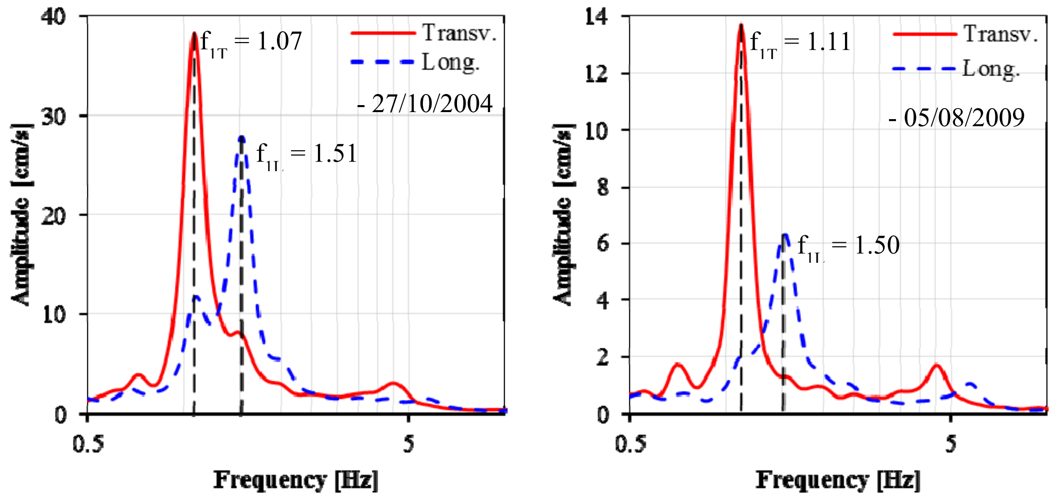

Fig. 5 – Fourier amplitude spectra of the top motions recorded during 27/10/2004 (M_W = 6.0) and 05/08/2009 (M_W = 5.5) earthquakes

The top/basement spectral ratios for the 27/10/2004 earthquake records and the average spectral ratios for all recorded events are shown in Fig. 6.

The first two translational modes on the transversal and longitudinal direction determined from spectral ratios are presented in Table 3. It can be seen that there is a small difference between the average modal frequencies and those estimated only from the spectral analysis of the 6.0 magnitude Vrancea earthquake records, indicating that the building experienced a linear dynamic behaviour during this moderate event.

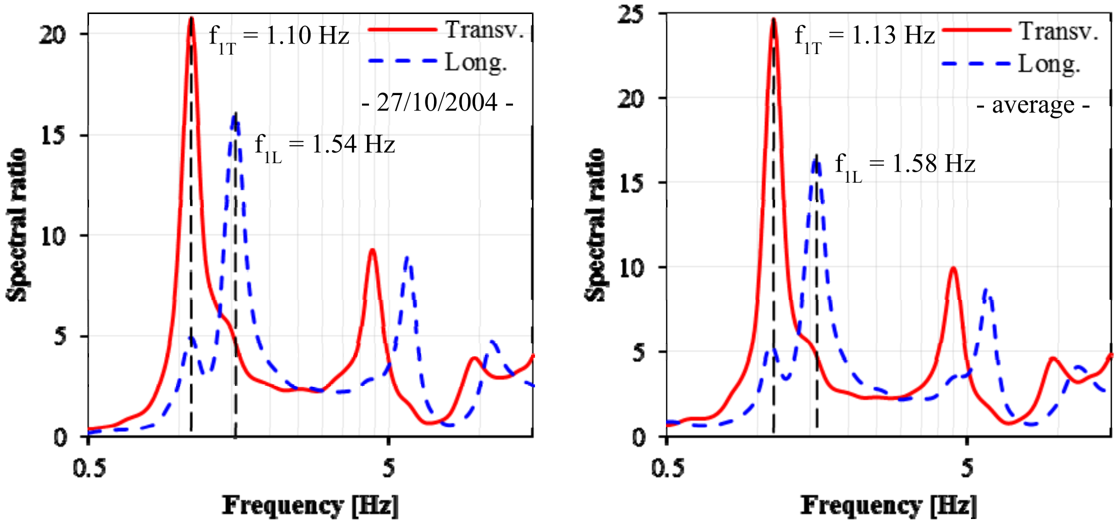

Fig. 6 – Spectral ratios for the 27/10/2004 (M_W= 6,0) earthquake and average spectral ratios

Table 3

Modal frequencies of the BRD building identified from spectral ratios

Nr.	Event			Spectral ratios			
				Transv. direction (T)		Long. direction (L)	
	Date	M_W	Δ [km]	f_1 [Hz]	f_2 [Hz]	f_1 [Hz]	f_2 [Hz]
1	21/01/2004	4.1	130.3	1.13	4.53	1.58	5.87
2	07/02/2004	4.4	147.9	1.15	4.54	1.57	5.85
3	10/07/2004	4.3	123.3	1.15	4.61	1.60	5.90
4	27/09/2004	4.6	139.2	1.15	4.53	1.58	5.85
5	27/10/2004	6.0	162.7	1.10	4.42	1.54	5.81
6	17/11/2004	4.4	152.0	1.13	4.56	1.57	5.87
7	14/05/2005	5.2	139.1	1.13	4.53	1.56	5.91
8	18/06/2005	5.0	162.6	1.15	4.56	1.59	5.95
9	08/09/2005	4.3	121.1	1.15	4.57	1.58	5.84
10	13/12/2005	4.8	158.0	1.12	4.48	1.58	5.84
11	18/12/2005	3.7	106.8	1.12	4.51	1.59	5.75
12	16/02/2006	4.1	147.3	1.12	4.54	1.59	5.83
13	06/03/2006	4.8	142.3	1.13	4.52	1.59	5.82
14	23/09/2006	4.3	123.8	1.13	4.46	1.58	5.88
15	17/01/2007	4.3	126.1	1.13	4.47	1.57	5.77
16	14/02/2007	4.2	120.7	1.13	4.50	1.58	5.74
17	25/04/2009	5.4	143.2	1.10	4.34	1.55	5.71
18	27/05/2009	4.4	138.5	1.14	4.42	1.58	5.80
19	05/08/2009	5.5	243.8	1.11	4.48	1.58	5.85
20	22/10/2009	3.7	140.4	1.10	4.52	1.56	5.83
21	26/12/2009	4.0	153.0	1.12	4.45	1.56	5.70
22	25/02/2010	3.7	132.0	1.11	4.50	1.57	5.86
23	08/06/2010	4.5	130.5	1.14	4.52	1.58	5.90
Average value [Hz]				1.13	4.50	1.58	5.83
Standard deviation [Hz]				0.02	0.06	0.01	0.06
Coefficient of variation [%]				1.77	1.33	0.63	1.03

A comparison between the results obtained from the Fourier amplitude spectra (FAS), the power spectral densities (PSD) and the top/basement spectral ratios is presented in Table 4.

Table ***Error! No text of specified style in document.***

Comparison between the average modal frequencies of the BRD building

Frequency [Hz]	FAS	PSD	Spectral ratios
f_{1T}	1.11	1.11	1.13
f_{2T}	4.49	4.50	4.50
f_{1L}	1.52	1.52	1.58
f_{2L}	5.74	5.74	5.83

5. Ambient vibrations and seismic records

35 ambient vibrations records were obtained between 2003÷2010 using the seismic sensors installed in the BRD-SG building. For example, ambient vibrations, on the transversal direction, recorded on a workday, are presented in Fig. 7.

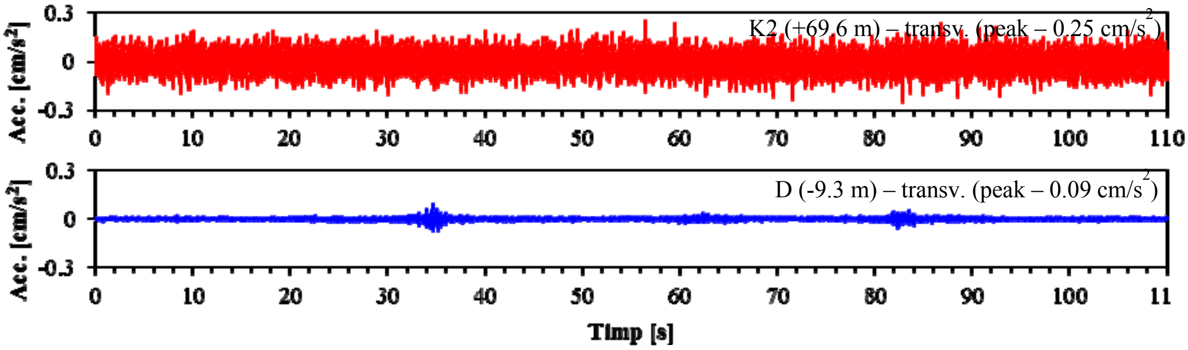

Fig. 7 – Ambient vibrations recorded at the top and basement of the BRD building, transversal direction

Comparisons between the average spectral ratios estimated from 35 ambient vibration records and from 23 seismic records are presented in Fig 8.

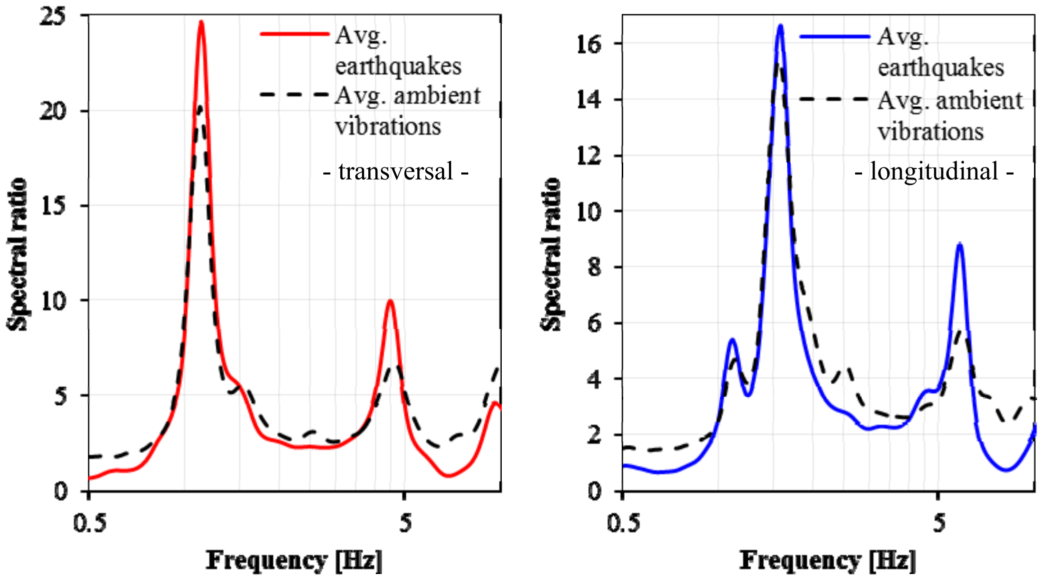

Fig. 8 – Comparisons between average ambient vibrations spectral ratios and average seismic spectral ratios

The similarity between the two average spectral ratios can readily be seen. The frequencies of the first translational modes of vibration identified from the ambient vibration records are: 1.12 ± 0.02 Hz on the transversal direction and 1.56 ± 0.03 Hz on the longitudinal direction.

The time evolution (2003÷2010) of the first translational modal frequencies, for the principal directions of the building, is shown in Fig.9.

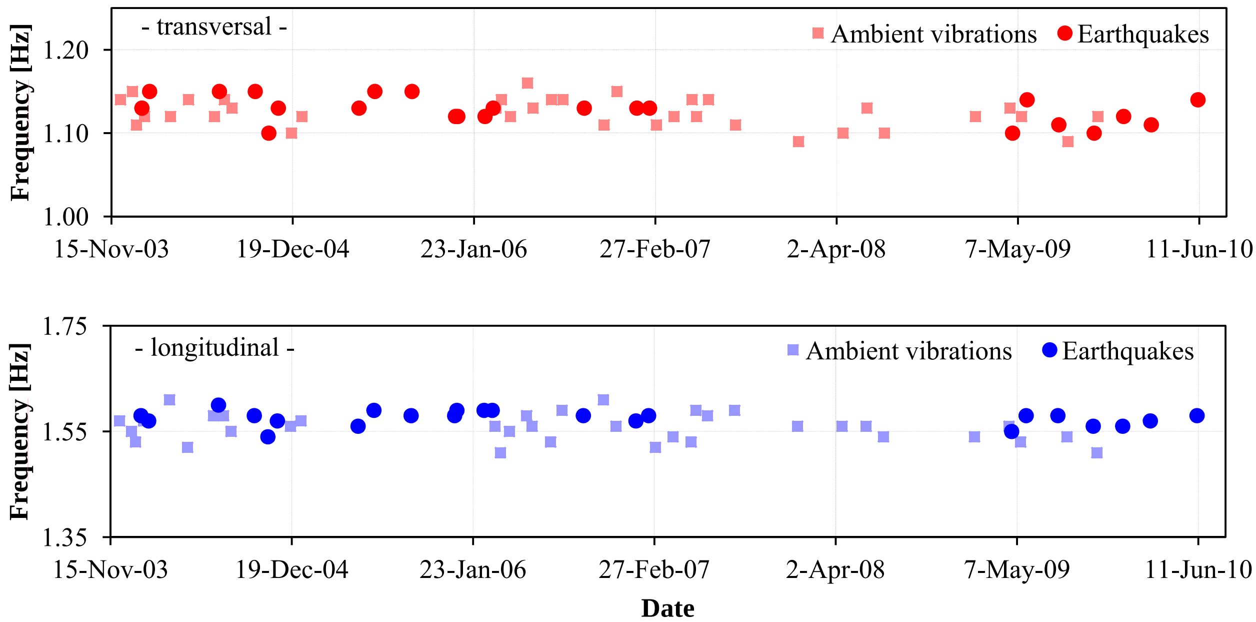

Fig. 9 – Time evolution of the first translational modal frequencies

The low variability of the modal frequencies identified from the seismic and ambient vibration records obtained in a monitoring period of 7 years (2003-2010), Fig. 9, indicates the stability of the dynamic characteristics of the building.

In 2002, at the request of the general contractor and of the structural designer, ambient vibration measurements were performed by UTCB using a network of portable velocity sensors. The modal frequencies of the building estimated in 2002: f_{1T} =1.12 Hz, f_{2T} = 4.53 Hz, f_{1L} = 1.56 Hz, f_{2L} = 6.09 Hz are in accordance with those obtained in the present study.

6. Conclusions

The modal frequencies of the BRD-SG building were identified from seismic and ambient vibration records, the results being valid in the buildings linear behaviour domain. For the two sets of instrumental data (seismic and ambient vibrations) recorded between 2003÷2010, the results from the frequency domain analysis are similar and in accordance with the results of previous studies [17], [18].

This case study represents a unique example in Romania of long-term monitoring (2002÷2010) of the dynamic characteristics of a tall building.

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