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EVIDENCE OF SOIL-STRUCTURE INTERACTION FROM EARTHQUAKE RECORDS AT A HIGH-RISE BUILDING SITE IN BUCHAREST

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ABSTRACT

The National Center for Seismic Risk Reduction (NCSRR, Bucharest, Romania) instrumented in 2003 in Bucharest a high-rise building with dual reinforced concrete structure (inner shear wall tube and perimeter frames, 3 under ground stories, ground floor and 18 stories above ground), designed and erected in 2001-2003. The seismic instrumentation (donated by Japan International Cooperation Agency JICA) consists of one seismic station with two tri-axial sensors for acceleration, one located at the top of the building and the other one on the foundation slab (third under ground storey). At about 100m near the building another station was installed by NCSRR, with tri-axial sensors at ground surface and in two boreholes at 28m and 151m depth. The building's dynamic characteristics were estimated using the recorded data from two Vrancea subcrustal source earthquakes that were simultaneously recorded at the building and at the nearby station (with ground surface & boreholes sensors): May 14th, 2005 (Mw=5.2) and Dec.13th, 2005 (Mw=4.8). It was observed that peak accelerations at the building 3rd basement level are sensibly smaller than the ground surface ones, during both earthquakes and for all recording directions. The "basement over ground surface" spectral ratios indicate a significant tendency of spectral amplitude reduction starting from frequencies of about 2-3Hz, phenomenon associated to kinematic SSI effects.

Keywords: kinematic soil-structure interaction, foundation input motion, earthquake records, NCSRR

INTRODUCTION

In 2002 the National Center for Seismic Risk Reduction (NCSRR, Bucharest, Romania) was created under the Ministry of Transports, Construction and Tourism, in order to implement the Japan International Cooperation Agency Technical Cooperation (JICA) Project with Romania entitled "Seismic risk reduction for buildings and structures"(JICA, 2002).

Within the Project, JICA donated to NCSRR seismic equipment (Kinemetrics) that was installed in 2003 together with specialists from OYO Seismic Instrumentation Corp., Japan. In 2005-2006 the seismic network was enlarged with Romanian efforts/investment, and other sites were instrumented with Geosig equipment and technical support. The NCSRR seismic network (Aldea et al., 2004, 2006) contains three types of instrumentation:
(i) free-field,
(ii) building, and
(iii) ground surface and boreholes.

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Two residential buildings of different structural systems located one near the other were instrumented in Central Bucharest. Two representative public buildings were also instrumented: The National Television Headquarters (that needs to be retrofitted) and the Headquarters of BRD-Société Générale Bank. These buildings were equipped in 2003 with K2 seismic stations and Episensor acceleration triaxial sensors from Kinemetrics. In 2006 the Technical University of Civil Engineering Bucharest main building was instrumented by NCSRR with two IA-1 Geosig stations (internet-based, with triaxial acceleration sensor) at top and in the basement.

In 2003 NCSRR installed in Bucharest seven K2 stations with sensors at ground surface and in boreholes at two levels of depth. At all these stations the soil profile of the boreholes is known and NCSRR and Tokyo Soil Research Co., Ltd. (Japan) performed down-hole tests. One of these stations (VIC) is located at about 100m from BRD building. At VIC location there is a station with ground surface sensor and two instrumented boreholes of 28m depth and of 151m depth. The borehole sensors are FBA-23DH from Kinemetrics. The locations of NCSRR seismic stations in Bucharest (highlighted are the BRD building and the free field & borehole VIC station) are presented in Fig. 1.

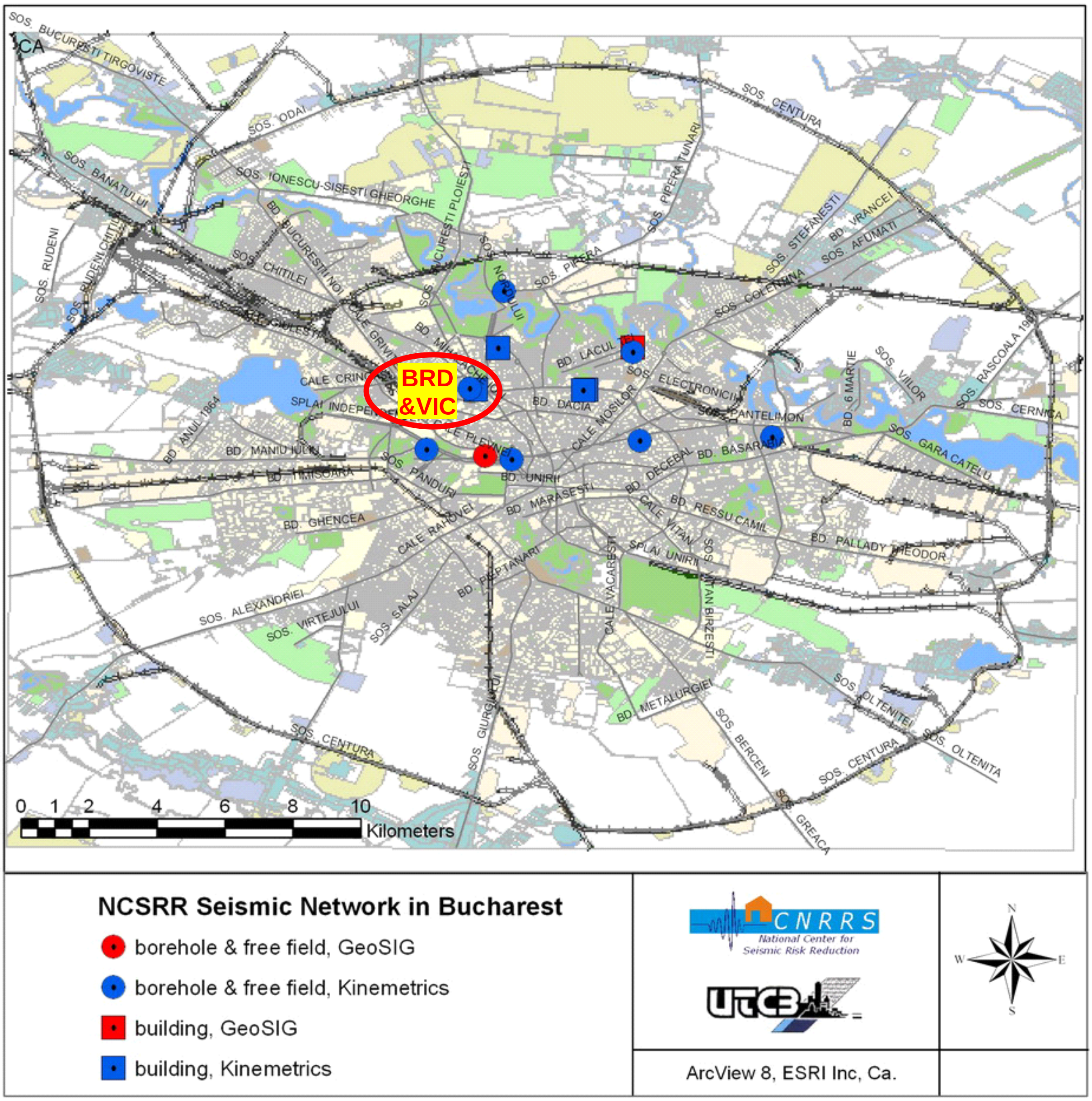


Figure 1. NCSRR seismic network in Bucharest

The modern new Headquarter of BRD-Société Générale Bank is shown in Photo 1. The BRD high-rise building was designed and erected in 2001 to 2003 and has a dual reinforced concrete structure (inner shear-wall tube and perimeter frames), with 3 underground stories, ground floor and 18 stories (Mironescu et al., 2003). Having 74m height, it is the second tallest building in Bucharest.

Photo 1. Headquarters of BRD-Société Générale Bank in Romania

The seismic instrumentation consists of one K2 Kinemetrics seismic station with two tri-axial sensors for acceleration (Episensor FBA ES-T), one at the top of the building (+69.6m) and the other one on the foundation slab (third underground storey, -9.3m). 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 of the building. The sensors horizontal recording axes correspond to the transversal T (NS) and longitudinal L (EW) directions of the building. In plane the buildings has about 26m on the short (transversal) direction and 54m on the long (longitudinal) direction.

The paper presents the analysis of two records that were simultaneously recorded in BRD building and at VIC seismic station (at ground surface and in boreholes). The analysis is made for the site response, the building response and the kinematic soil-structure interaction effects are investigated.

RECORDS FROM VRANCEA SUBCRUSTAL EARTHQUAKES

Romania is an earthquake prone country, its seismic activity being dominated by Vrancea intermediate depth (60÷170km) source, and by several crustal sources. Vrancea source governs seismic hazard not only in Romania but also in Republic of Moldova and also affects large areas of Bulgaria and Ukraine.

Since its installation, the NCSRR network recorded more than 130 seismic motions from 22 earthquakes with moment magnitudes ranging from M_W=3.2 to 6.0. From these earthquakes, 17 are from Vrancea subcrustal source, 2 from Vrancea crustal source, 2 from shallow sources in Bulgaria and 1 from North-Dobrogea shallow source. In the buildings instrumented by NCSRR were obtained 33 records, all of them due to earthquakes from Vrancea subcrustal source.

At BRD seismic station were recorded 13 earthquakes, all from Vrancea subcrustal source, having magnitude in between M_W=3.7 and 6.0. At VIC station were recorded 3 earthquakes, all from Vrancea subcrustal source, having magnitude in between M_W=4.6 and 5.2.

During the May 14th, 2005 (Mw=5.2) and the Dec.13th, 2005 (Mw=4.8) earthquakes, simultaneous data were recorded at BRD building and at the nearby VIC seismic station (with ground surface & boreholes sensors). In Table 1 are presented the peak accelerations at these seismic stations (considering only the S-wave part of the motions), and in Figure 2 are presented the NS components of ground motion during the May 14^{th}, 2005 event.

Table 1. Peak accelerations at BRD building and VIC seismic stations

Sensor disposal		Peak acceleration (S-wave part of the motion), cm/s^2					
		May 14th, 2005 (*Mw*=5.2)			Dec.13th, 2005 (*Mw*=4.8)		
Location	Level, m	EW (L)	NS (T)	V	EW (L)	NS (T)	V
top of building	69.6	14.1	14.7	6.0	13.5	28.0	8.8
3^{rd} basement	-9.3	5.1	3.6	1.3	4.1	7.7	1.9
ground surface	0	12.8	18.2	5.4	12.7	20.1	6.1
shallow borehole	-28	4.7	5.3	2.5	4.6	7.6	3.4
deep borehole	-151	3.4	3.3	1.6	3.8	5.8	1.9

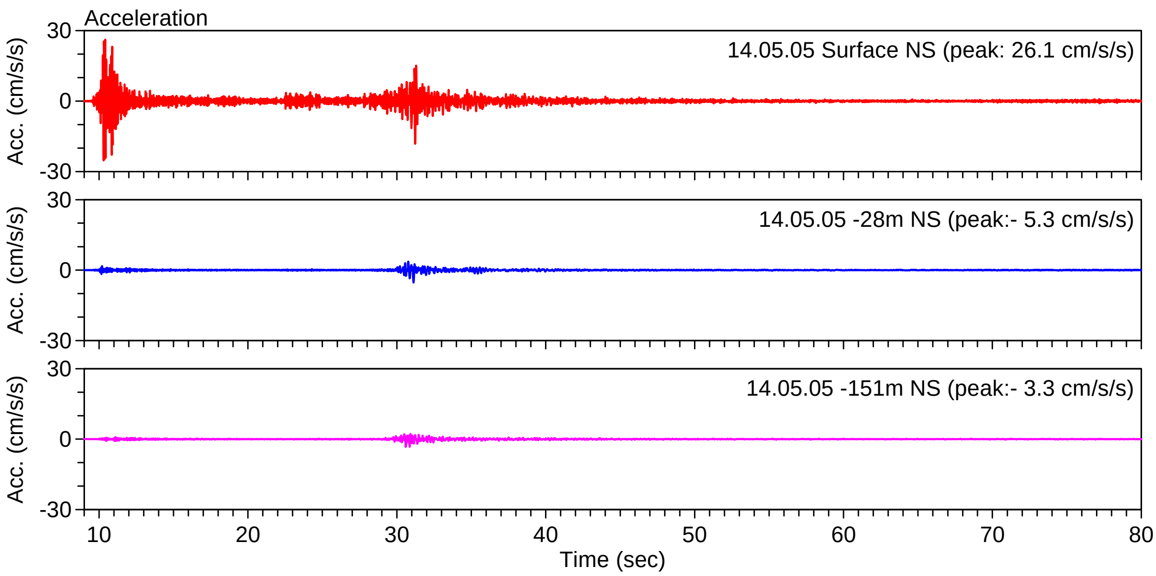


Figure 2. Seismic records at ground surface & in boreholes at VIC station (14.05.05 earthquake)

Analysis of VIC station records (ground surface and boreholes)

In Figure 3 are presented the H/V Fourier amplitude spectral ratios at ground surface and the Surface-over-borehole Fourier amplitude spectral ratios (SBSR) for the records at VIC station during the 14.05.05 (Mw=5.2) and the 13.12.05 (Mw=4.8) events.

The H/V ratios indicate a soil response having an important content of low frequencies (below 1Hz), a peak close to 1Hz is present during both earthquakes, and a lower peak appears at 0.4-0.6Hz.

The SBSR ratios characterize only the response of the soil column from -151m to the ground surface. The ratios explicitly indicate a low frequency response, with clear and stable peak bellow 1 Hz. The first frequency peaks identified from SBSR ratios are indicated in Table 2, and one can observe the good overall stability during the two events.

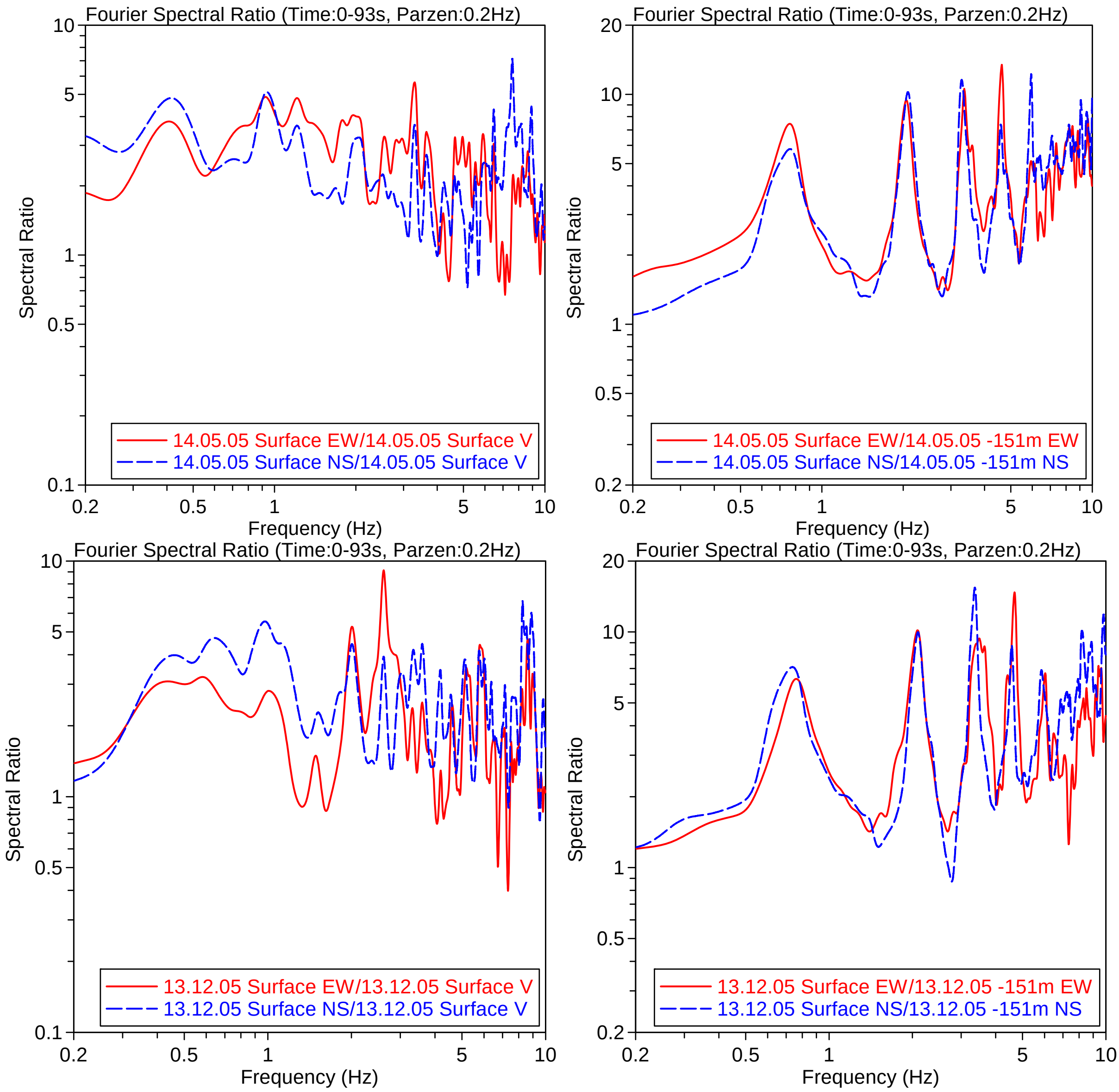


Figure 3. H/V and SBSR at VIC seismic station

Table 2. Peak frequencies at VIC seismic station from surface-to-borehole spectral ratios

Earthquake		SBSR peak frequencies, Hz			
		f_1	f_2	f_3	f_4
May 14th, 2005 (*Mw*=5.1)	EW	0.76	2.05	3.36	4.63
	NS	0.76	2.08	3.29	4.59
Dec.13th, 2005 (*Mw*=4.8)	EW	0.76	2.09	3.48	4.67
	NS	0.74	2.09	3.36	4.56

In Figure 4 (left) are presented comparatively the SBSR ratios between the ground surface and the deep borehole and between the shallow borehole and the deep one, in order to investigate the influence of the shallow soil layers on the site response. From Table 1 one can observe the significant increase of peak ground acceleration from -28m to the surface, while from -151m to -28 m the peak values are almost the same. From Figure 4 (left) it can be observed that the soil column response frequencies are not influenced by the top layer, their positions on the frequency axis being identical in both ratios. The first peak has even similar amplitude, but in high frequency domain there is an amplitude increase for the ground motion at surface, that explains also the amplification of peak ground acceleration (associated to high frequency components of ground motion).

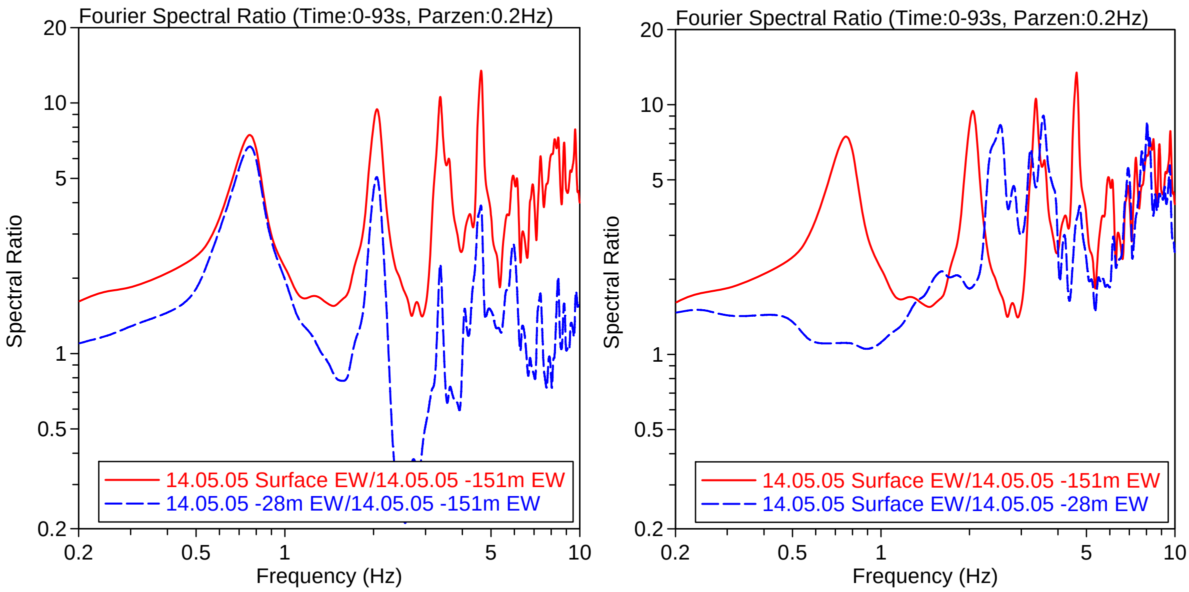


Figure 4. SBSRatios at VIC seismic station

Figure 4 (right) shows the SBSR ratios between ground surface and -151m, and ground surface and -28m. It can be observed that the evaluation of site response using only top ~30m of soil can't catch the global site response. However, Figure 4 indicates that the top soil layers bring an amplification of site response in the high frequency domain, which leads to an increase of peak ground acceleration.

The soil profile at VIC station was investigated by down-hole test in 2003 by NCSRR and Tokyo Soil Research Corp. (Aldea et al., 2006). The shear wave velocity profile up to 110m depth obtained from measurements is presented in Table 3. In all cases of averaging shear wave velocity (i.e. using different soil profile thickness: 30m, 52m, 110m), the site is classified as "hard soil"-class D according to UBC 1997, and "Deep deposits of dense or medium dense sand, gravel or stiff clay with thickness from several tens to many hundreds of m" class C according to EC 8. There is a clear decrease of soil column approximate frequency with the increase of considered depth, the value for 110m of soil profile getting closer to the one obtained from SBSR ratios using earthquake records.

Table 3. Shave wave velocity profile at VIC seismic station

Velocity profile	h (m)	Vs (m/s)
	3	180
	7	280
	14	300
	15	350
	11	350
	9	390
	12	370
	19	420
	14	420
	6	420
Investigated depth, m	110	
Average *Vs* (30m), m/s	284	
Predominant frequency (30m), Hz	2.38	
Average *Vs* (52m), m/s	310	
Predominant frequency (52m), hz	1.49	
Average *Vs* (110m) , m/s	354	
Predominant frequency (110m), Hz	0.81	

Analysis of BRD building records

As an example, for the 14.05.2005 Vrancea earthquake (Mw=5.2), the recorded horizontal motions at basement and top of the building are comparatively represented in Figure 5.

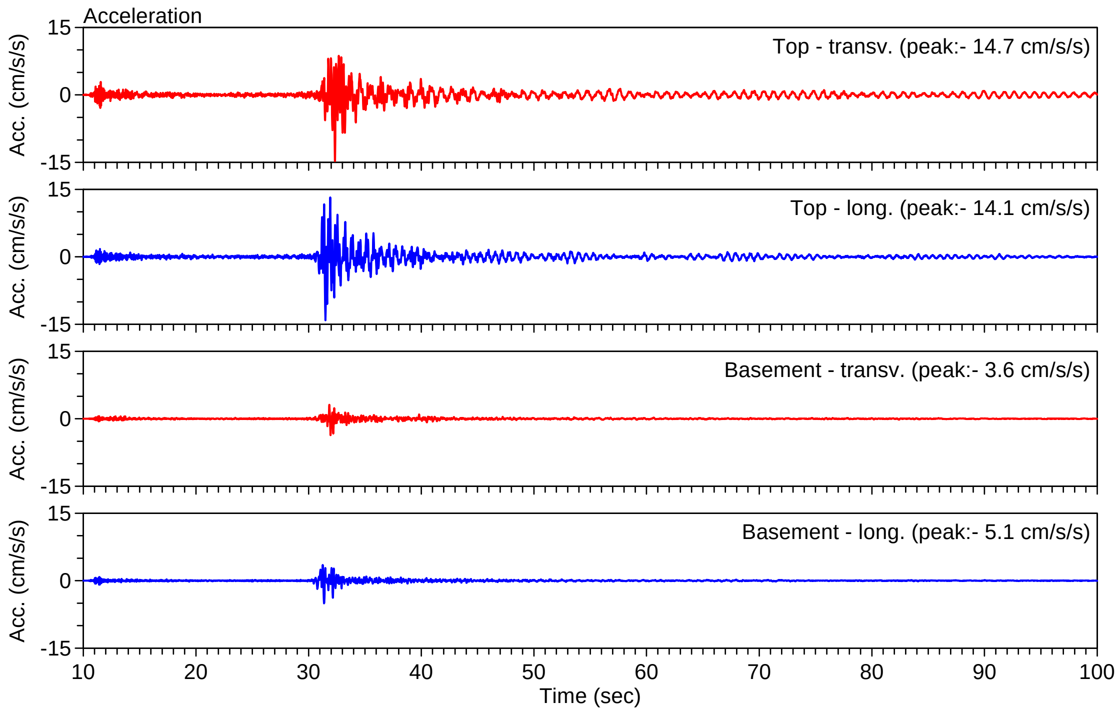


Figure 5. Vrancea earthquake of 14.05.05 - recorded seismic motions at BRD building

The modal frequencies are identified from the top over basement spectral ratios (Figure 6), and they can also be estimated from the Fourier amplitude spectra of top motion (Celebi, 2004). The first modal frequencies identified from top over basement ratios are given in Table 4 (where f_{1T} is the first modal frequency on transversal direction and f_{2T} is the second one, f_{1L} is the first modal frequency on longitudinal direction and f_{2L} is the second one).

Table 4. Modal frequencies of BRD building identified from earthquake records

Event			Transversal (*T*) direction				Longitudinal (*L*) direction			
Date	Mw	Δ, km	f_{1T}, Hz	f_{1L}	f_{2T}	f_{2L}	f_{1T}, Hz	f_{1L}	f_{2T}	f_{2L}
14/05/2005	5.2	*139*	*1.14*	*1.51*	*4.56*		*1.09*	*1.58*	*4.47*	*5.90*
13/12/2005	4.8	*158*	*1.13*		*4.50*	*5.91*	*1.09*	*1.57*	*4.47*	*5.79*

The results are in good agreement with the data obtained from the spectral analysis of the BRD acceleration records obtained from all 13 Vrancea subcrustal earthquakes (Demetriu & Aldea, 2006): on transversal direction 1.12Hz ± 0.02Hz and 4.57Hz ± 0.07Hz; on longitudinal direction 1.56Hz ± 0.05Hz and 5.58Hz ± 0.07Hz.

The seismic instrumentation from BRD building was also used for recording ambient vibrations (Negulescu *et al*., 2004), and the first modal peaks were found at 1.14Hz on transversal direction and at 1.59Hz on longitudinal direction.

In December 2002, at the request of the general contractor and of the structural designer of BRD building, ambient vibration measurements were performed by Technical University of Civil Engineering Bucharest [Aldea *et al*., 2002], using velocity sensors. There is a good agreement between the results obtained using earthquake records (presented above) and the results from ambient vibration velocity records: f_{1T} (transversal) = 1.12 Hz, f_{1L} (longitudinal) = 1.56 Hz, f_{2T} (transversal) = 4.53 Hz, f_{2L} (longitudinal)=6.09 Hz.

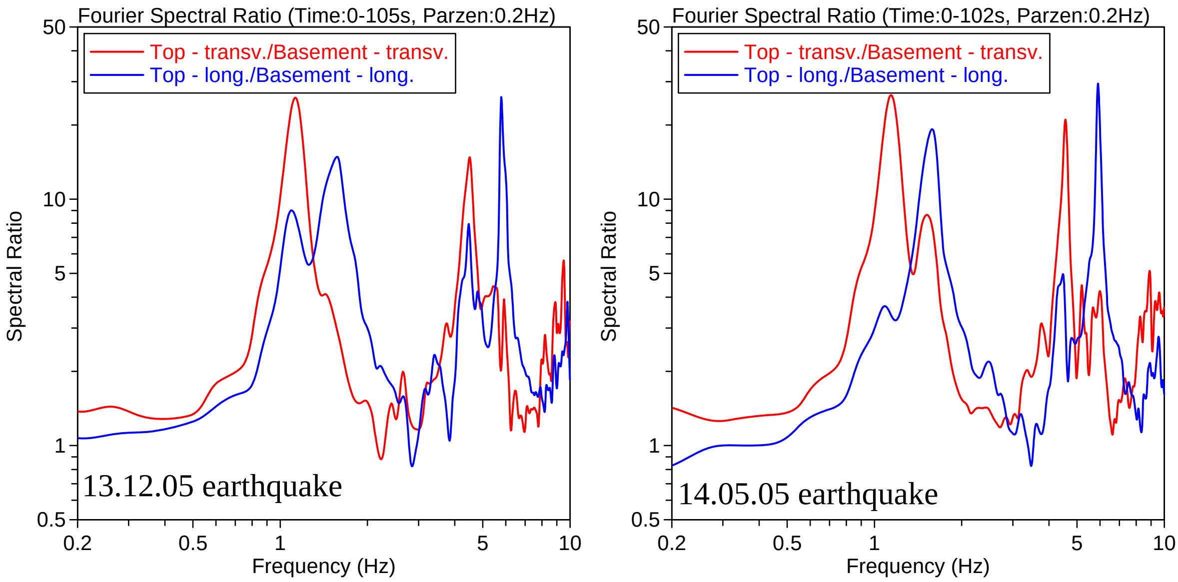


Figure 6. Top over basement spectral ratios at BRD building

SSI EFFECTS FROM BUILDING RECORDS AND FREE-FIELD RECORDS AT BRD SITE

From Table 1 it is observed that the peak accelerations at the building 3rd basement level are sensibly smaller than the ground surface ones, during both earthquake events and for all recording directions. In Figure 7 are presented the horizontal accelerations recorded at ground surface and at the 3rd building basement during the 14/05/2005 earthquake.

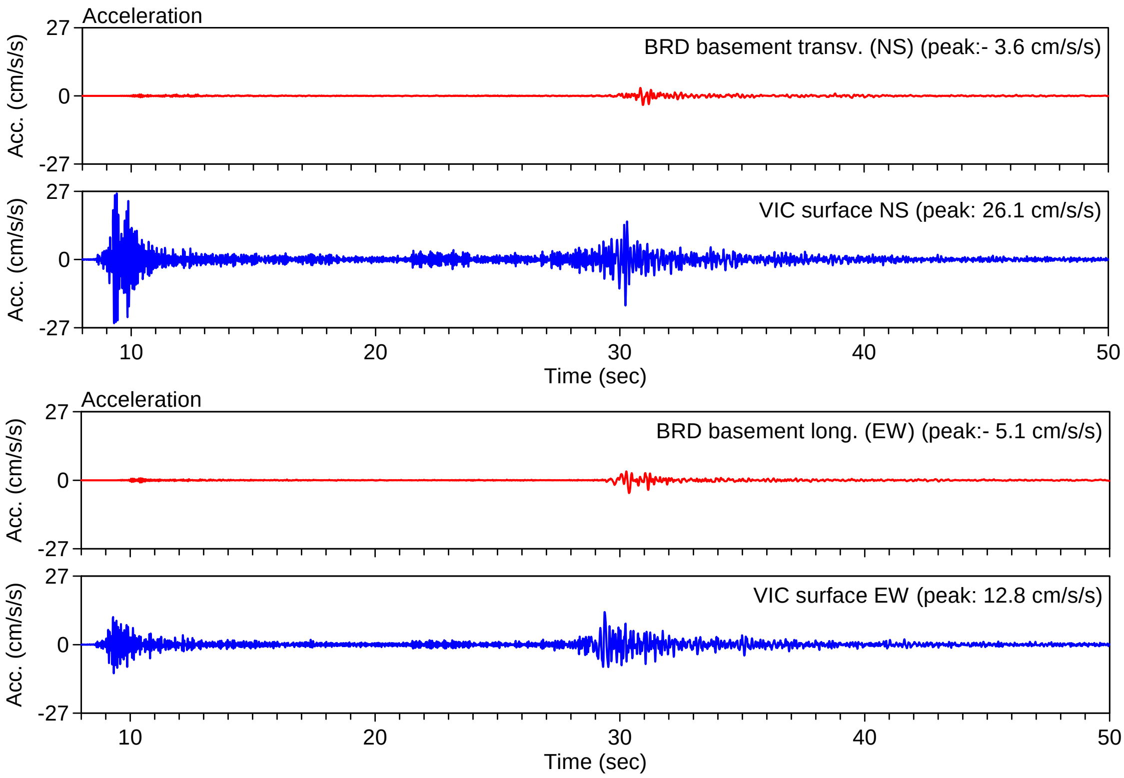


Figure 7: Horizontal accelerations recorded at ground surface and at the 3rd basement of BRD building during the 14/05/2005 Vrancea earthquake

The differences between the motions at ground surface and at the 3rd building basement revealed by Figure 7 and Table 2 are indicating the existence of kinematic soil-structure-interaction effects (SSI).

These kinematic soil-structure-interaction effects are further investigated in frequency domain. In Figure 8 are plotted the Fourier amplitude spectra of the recorded accelerograms during the two earthquakes. There is a significant tendency of spectral amplitude reduction at high frequencies, phenomenon associated to SSI effects and reported in literature (Iiba, 1998, Zhao , 1998, etc.). In Figure 9 are presented the basement over ground surface spectral ratios for these seismic events.

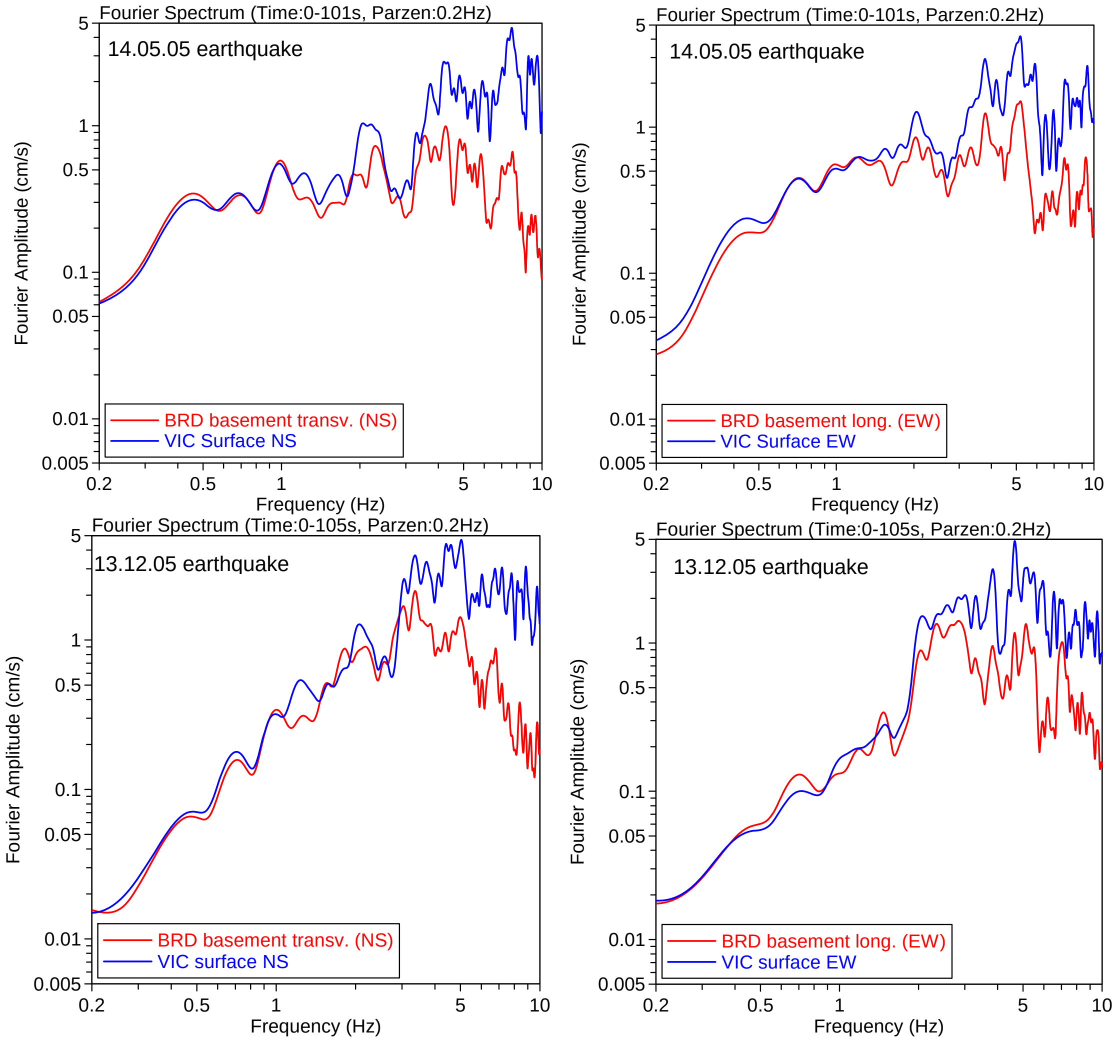


Figure 8: Fourier amplitude spectra of the recorded motions

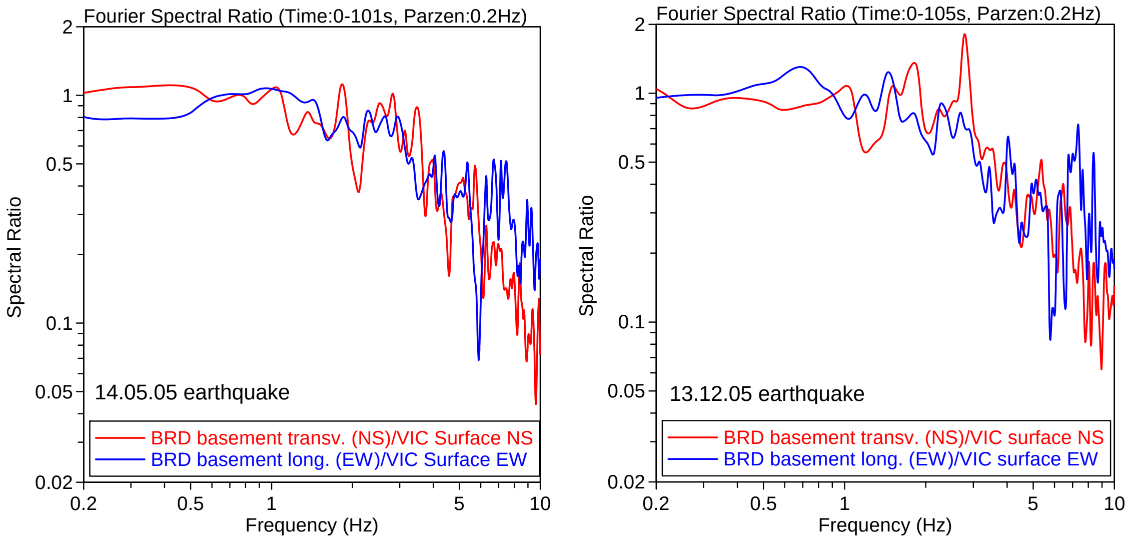


Figure 9: Basement over ground surface spectral ratios

Basement motion decreased in comparison with the ground surface motion due to the rigidity and embedment of building foundation (filtering effect). The spectral ratios display a less than unit ratio starting from frequencies of about 2-3Hz. The reduction of input motion at basement of buildings due to kinematic soil-structure interaction represents an actual research subject, several studies proposing or discussing relations for the reduction function in frequency domain, as for example Elsabee and Morray (1977), Harada et al. (1981 and 1985) and Stewart (1998, 2004).

For the reduction of translation (horizontal) motion, Harada et al. proposed the following relation:

$$H_{hh}(\omega) = \begin{cases} \left[\dfrac{\sin(\omega e/Vs)}{\omega e/Vs}\right]^2, & \omega \le \omega_n \\ 0.405, & \omega > \omega_n \end{cases} \quad (1)$$

where e is the embedment depth of the foundation, m

Vs - the average shear wave velocity, m/s

ω - circular frequency, radians

$\omega_n = \dfrac{\pi Vs}{2e}$.

Elsabee and Morray (1977) proposed the following relation (for translation motion of circular foundation):

$$H_u(\omega) = \begin{cases} \cos\left(\dfrac{e}{r}\cdot a_0\right), & a_0 \le 0.7\overline{a}_0 \\ 0.453, & a_0 > 0.7\overline{a}_0 \end{cases} \quad (2)$$

where e is the embedment depth of the foundation

r - foundation radius

$a_0 = \dfrac{\omega \cdot r}{Vs}$

ω - circular frequency

Vs - average shear wave velocity from surface to embedment depth e

$\overline{a}_0$ - is the normalized frequency that corresponds to the fundamental frequency of the soil from surface to embedment depth e ($\overline{a}_0 = \dfrac{2\pi\ f_1\ r}{Vs}, \quad f_1 = \dfrac{Vs}{4e}$).

For exemplification, Harada (1981, 1985) and Elsabee and Morray (1977) were applied for BRD building and soil, and are represented for comparison in Figure 10 together with the observed spectral ratios from Figure 9. The average shear wave velocity was considered as follows: for Harada et al. Vs=284m/s (average over 30m), for Elsabee and Morray Vs=242m/s (average over 10.5m). The embedment depth is 10.5m. As it can be observed, the real data reduction tendency with increasing frequency is similar to that from the proposed formulas.

In Fig.11 are shown the ratios between Fourier amplitude spectrum at top of BRD building and Fourier amplitude spectrum at ground surface at VIC station. The first modal frequencies identified by the ratios in Figure 11 are somehow smaller than the ones obtained from the top/basement spectral ratios (Table 4, Fig.6): on transversal direction 1.09-1.11Hz instead of 1.13-1.14Hz, and on longitudinal direction 1.49Hz instead of 1.56Hz. This is also due to SSI (inertial effect) but the differences are so small that it can be considered that inertial SSI effects are negligible.

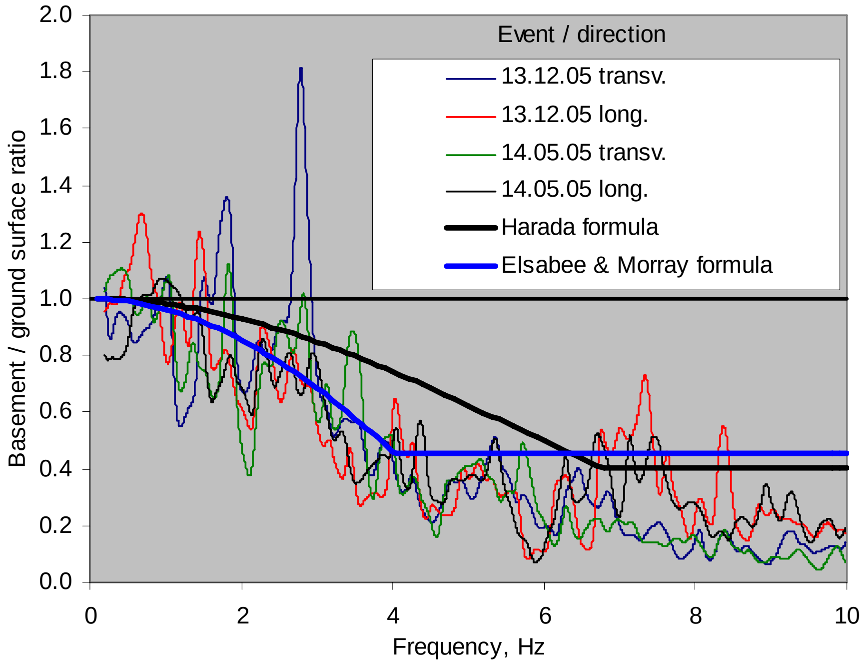
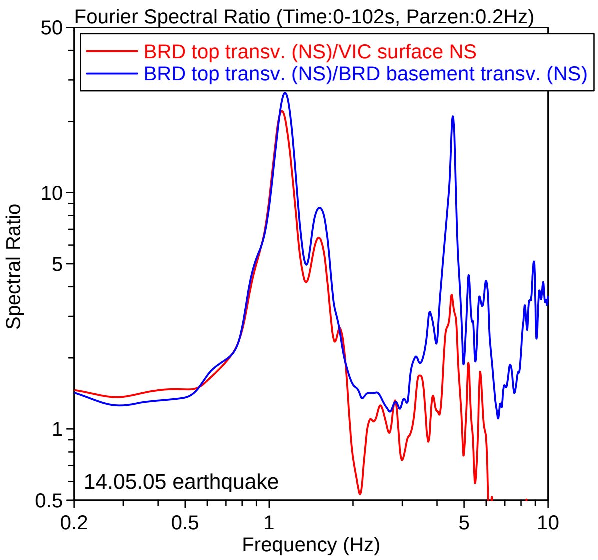


Figure 10: Comparison between observed basement over ground surface spectral ratios and Harada et al., and Elsabee & Morray reduction formulas



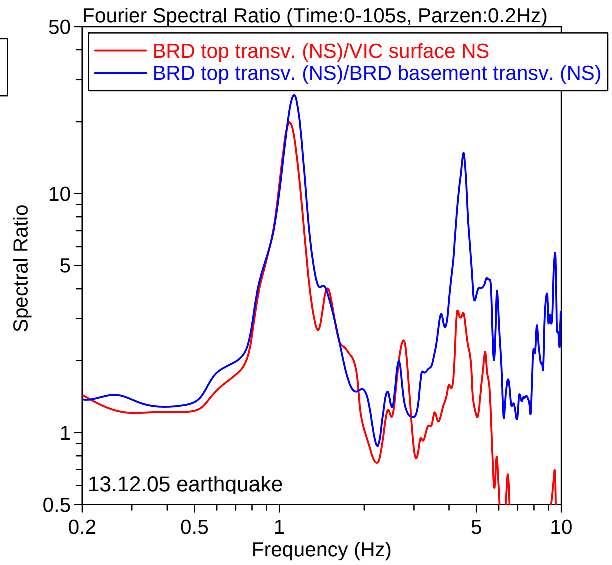


Figure 11: Spectral ratios beween motion at top of BRD building and ground surface motion

CONCLUSIONS

The site response at VIC site indicated low frequency components, with a strong peak at ~0.8Hz. The building dynamic characteristics were in agreement with a previous study that used all earthquake records available at BRD building and with studies using ambient vibrations (velocity or acceleration). Based on the simultaneous records at ground surface and at the building's basement, it was observed that peak accelerations at the building 3rd basement level are sensibly smaller than the ground surface ones, during both earthquakes and for all recording directions. The "basement over ground surface" spectral ratios indicate a significant tendency of spectral amplitude reduction starting from frequencies of about 2-3Hz, phenomenon associated to kinematic SSI effects. The available NCSRR seismic instrumentation offers useful data for soil-structure interaction effects in Bucharest.

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REFERENCES

Aldea, A.,Yamanaka, H., Negulescu, C., Kashima, T., Radoi, R., Kazama, H., Calarasu, E., "Extensive seismic instrumentation and geophysical investigations for site-response studies in Bucharest, Romania", *ESG 2006 Third International Symposium on the Effects of Surface Geology on Seismic Motion*, Grenoble, France, 30 Aug.-1 Sept., Paper Number: 69, 10p, CD-ROM, 2006

Aldea, A., Kashima, T., Lungu, D., Vacareanu, R., Koyama, S., Arion, C., "Modern Urban Seismic Network in Bucharest, Romania", *Proceedings of the First International Conference on Urban Earthquake Engineering*, March 8-9, Tokyo Institute of Technology, Yokohama, Japan, 8p., 2004

Aldea, A., Demetriu, S., Sandu, C., Vacareanu, R., Arion, C., "Ambient vibration measurements and dynamic identification for "Tour Place de la Victoire (BRD-S.G. headquarters)", Contract nr.281/2002 at *Technical University of Civil Engineering Bucharest* & nr.117/2002 at BIP S.A., 74p., 2002 (in Romanian)

Celebi, M., "Response of a 14-story Anchorage, Alaska, Building in 2002 to two close earthquakes and two distant Denali fault earthquakes", *Earthquake Spectra*, Vol.20, No.3, p.693-706, 2004

Demetriu, S., Aldea, A., 2006. "Recorded Seismic Response of an Instrumented High-Rise Reinforced-Concrete Building in Bucharest", *1st ECEES First European Conference on Earthquake Engineering and Seismology*, Geneva, Switzerland, 3-8 September 2006, Paper Number: 777, 10p., CD-ROM

Elsabee, F., Morray, J.P., "Dynamic behavior of embeded foundations", Report no. R77-33, Dept.of Civil Engineering, *MIT*, Cambridge, Mass., 1977

Harada, T., Kubo, T., Katayama, T., "Dynamic soil-structure interaction analysis by continuum formulation method", Report of the *Institute of Industrial Science, The University of Tokyo*, Vol. 29, No.5, March, 56p, 1981

Harada, T., Kubo, T., Katayama, T., "Model of the effective seismic motions of embedded foundation and its verification by observed data", *Journal of Japanese Society of Civil Engineers*, No.362, p.435-440, 1985 (in Japanese)

Iiba, M., Watakabe, M., Fujii, A., Koyama, S., Sakai, S., Morita, K., "A study on Dynamic Soil Structure Interaction Effect Based on Microtremor Measurements of Building and Surrounding Ground Surface", *Proceedings Third UJNR Workshop on Soil-Structure Interaction*, March 29-30, , Menlo Park, 17p., 2004

Negulescu C., Radoi, R., Aldea, A., "Report on microtremor measurement for evaluation of building vibration characteristics", *National Center for Seismic Risk Reduction*, Bucharest, 19p., 2004

Mironescu, M., Stanescu, A., Brotea, T., Bortnowski, A., Sava, V., Comanescu, R., "Modeling, configuration and analysis for high importance buildings", *Bulletin of the Association of Structural Design Engineers AICPS*, Bucharest, Romania, No.3, p.1-17, 2003 (in Romanian)

Stewart, J.P., Seed, R.B., Fenves, G.L., "Empirical evaluation of inertial soil-structure interaction effects", Report No. PEER-98/07, *Pacific Earthquake Engineering Research Center*, University of California, Berkeley, 209 p., 1998

Zhao, J.X., "Estimating kinematic interaction of raft foundations from earthquake records and its effects on structural response", *Soil Dynamics and Earthquake Engineering* 17, 73-88, 16p., 1998