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FREE-FIELD AND BOREHOLE STRONG MOTION ARRAY IN BUCHAREST, ROMANIA

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ABSTRACT

In the frame of the Japan International Cooperation Agency (JICA) seismic risk reduction project in Romania, the National Center for Seismic Risk Reduction (NCSRR, Bucharest) instrumented in 2003 seven sites in the northern half of the capital of Romania, Bucharest. The JICA donated instrumentation (Kinemetrics) consists at each site of one acquisition station and 3 triaxial sensors: one in free-field (ground surface) and two in boreholes - one shallow borehole (around 30m depth) and one deep borehole (with depths ranging from 50m to 153m). The network recorded until now 64 ground motions from 21 earthquakes with moment magnitudes ranging between 3.7 and 6. In 2005 another site was instrumented with a Geosig station (with triaxial sensors at free-field and in a 30m depth borehole) using Romanian funding. The seismic data is accompanied by velocity profiles at all the sites, determined by NCSRR in cooperation with Tokyo Soil Research Co., Ltd., in 2003-2005 by down-hole tests, using equipment donated by JICA. The NCSRR seismic network provides useful information for the site-response assessment in Bucharest. It also provides earthquake data for estimating the amplifications due to the upper 30m of sediments, which is of interest for checking the site classification and their corresponding spectra from design codes. Located in Bucharest, a European capital-city with high seismic risk exposed to Vrancea subcrustal earthquakes, the NCSRR seismic network (with 15 instrumented boreholes at 8 sites where ground surface sensors are also available) offers a valuable site for the evaluation of ground motion amplification.

Keywords: accelerometer array, borehole seismic instrumentation, Bucharest, NCSRR, JICA

NCSRR SEISMIC NETWORK IN BUCHAREST

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, USA) 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 equipment and technical support from Geosig, Switzerland. The NCSRR seismic network (Aldea *et al.*, 2004, 2006a) contains three types of instrumentation: (i) free-field stations outside Bucharest, (ii) building stations in Bucharest, and (iii) stations with free-field/ground surface and boreholes sensors in Bucharest.

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NCSRR installed in 2003 in Bucharest seven acquisition stations with sensors at ground surface (mostly in free-field conditions) and in boreholes at two levels of depth: at ~30m depth and between 50m and 153m depth, Table 1. In 2005 another site was instrumented with GeoSIG equipment (free-field & a 30m depth borehole). Table 1 briefly describes the stations (their location is given in Fig. 1).

Table 1. NCSRR free-field and borehole seismic stations in Bucharest

No.	Site	Station ID	Surface sensor location	Depth of sensor in shallow borehole, m	Depth of sensor in deep borehole, m	Type of equipment
1	UTCB Tei	UTC1	free field	-28	-78	K2 + FBA-23DH (Kinemetrics)
2	UTCB Pache	UTC2	1 storey building	-28	-66	
3	NCSRR/INCERC	INC	1 storey building	-24	-153	
4	Civil Protection Hdq.	PRC	1 storey building	-28	-68	
5	Piata Victoriei	VIC	free field	-28	-151	
6	City Hall	PRI	free field	-28	-52	
7	Municipal Hospital	SMU	free field	-30	-70	
8	UTCB Plevnei	UTC3	free field	-30	-	GSR24+AC23 DH (Geosig)

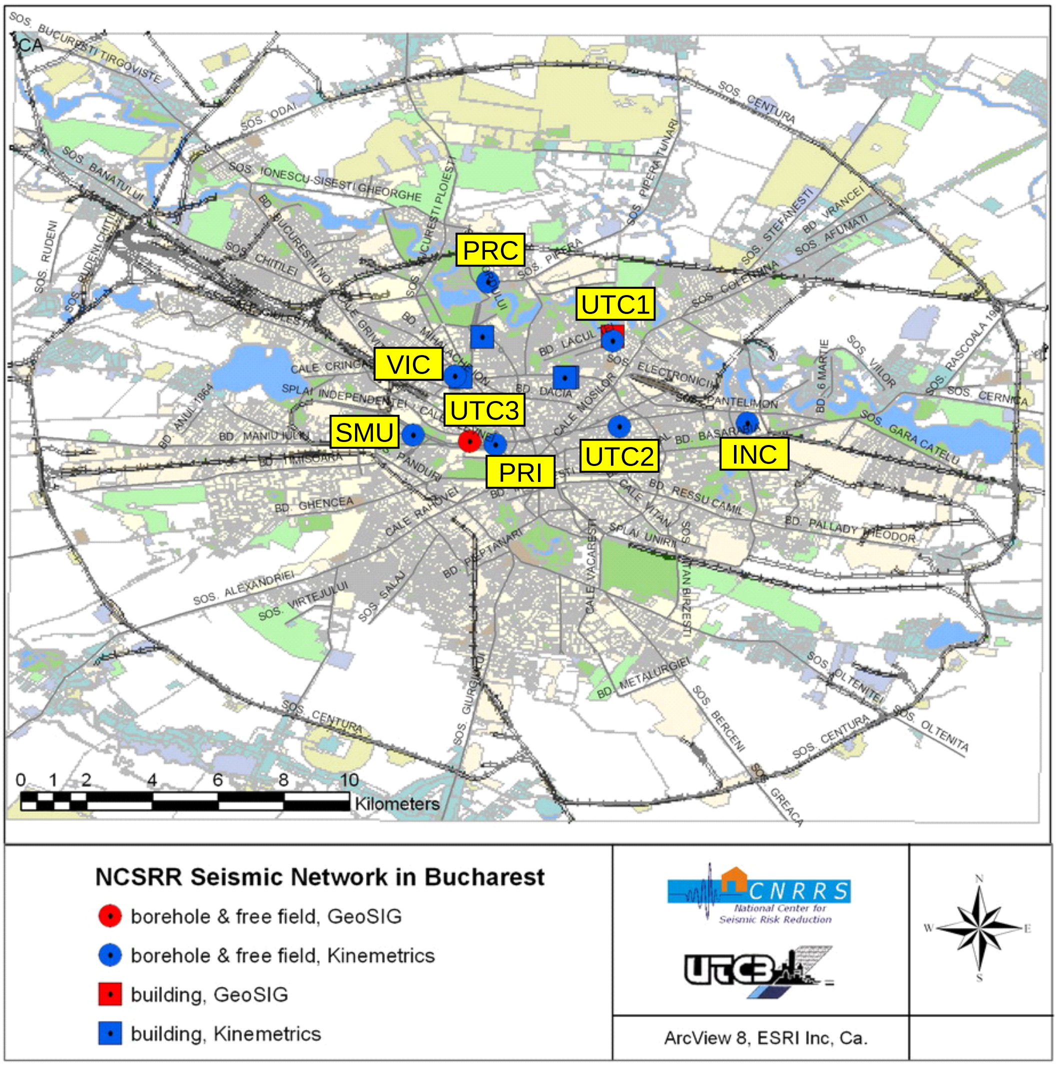

Figure 1. NCSRR seismic network in Bucharest

GROUND CONDITIONS AT SEISMIC STATIONS SITES

At all the stations the soil profile/stratigraphy of the boreholes is known, and NCSRR and Tokyo Soil Research Co., Ltd. performed in 2003 down-hole tests for the estimation of the seismic velocities profiles at all sites (Aldea *et al.*, 2006b). In Table 2 are presented the weighted average (UBC formula) shear wave velocity (Vs) for seven sites (using the upper 30m and the upper 52 m of soil). One can observe that the differences between the sites are not significant when looking at the average on 52m and some differences (up to 50%) exists at the average on 30m. In all cases the sites are 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 Eurocode 8. Array microtremor measurements were used for the trying to establish a velocity profile down to the seismic bedrock; preliminary results are shown in Aldea *et al.*, 2006c, and Yamanaka *et. al*, 2007. These studies indicated that the quaternary deposits have ~250÷350m thickness; the thickness is increasing from southern part to northern part of the city, and the shear wave velocity of the quaternary deposits is <500m/s. Probably the deeper deposits from Pliocene and Miocene also influence the characteristics of site response, the higher vibration modes should not be neglected when studying site response (Yamanaka *et al.*, 2007), but further studies are need.

Table 2. Average shear wave velocity at NCSRR stations based on down-hole tests

Station	PRI	SMU	INC	VIC	UTC2	PRC	UTC1
Average *Vs* (30m), m/s	219	245	270	284	288	293	309
Average *Vs* (52m), m/s	258	281	302	310	318	309	326

EARTHQUAKE RECORDS

Since its installation, the NCSRR network (all types of instrumentation) recorded more than 130 seismic motions from 24 earthquakes with moment magnitudes ranging from 3.2 to 6.0. From these earthquakes, 19 are from Vrancea subcrustal source (focal depth between 60 and 170 km), 2 from Vrancea crustal source, 2 from shallow sources in Bulgaria and 1 from North-Dobrogea shallow source.

The seismic stations in Bucharest having borehole instrumentation (Table 1) recorded data only from 21 seismic events that described in Table 3 (their location map is shown in Figure 4).

The distribution of records obtained at the seismic stations with borehole instrumentation in Bucharest, according to the seismic source is presented in Table 3.

Table 3. Distribution of seismic records at NCSRR stations with boreholes in Bucharest

Earthquake source	No. of recorded earthquakes	No. of records
Vrancea subcrustal	18	58
Bulgaria shallow	2	5
North Dobrogea shallow	1	1
Total	21	64

Records from October 27, 2004 Vrancea subcrustal earthquake (M_w =6.0)
In Bucharest all stations with boreholes recorded the Oct.27, 2006 earthquake (*Mw*=6) except VIC one (due to the absence of electric supply). The recorded peak ground accelerations *PGA* are presented in Table 5. A certain variability within the city can be observed, with highest values in the vicinity of Dambovita river (PRI and SMU), and with the lowest value in eastern Bucharest (INC). It can be noticed that the top ~30m of soil had the most important contribution for the level of the horizontal *PGA* by at least doubling the recorded values, while from the deep borehole to the shallow one there are no major changes of peak accelerations.

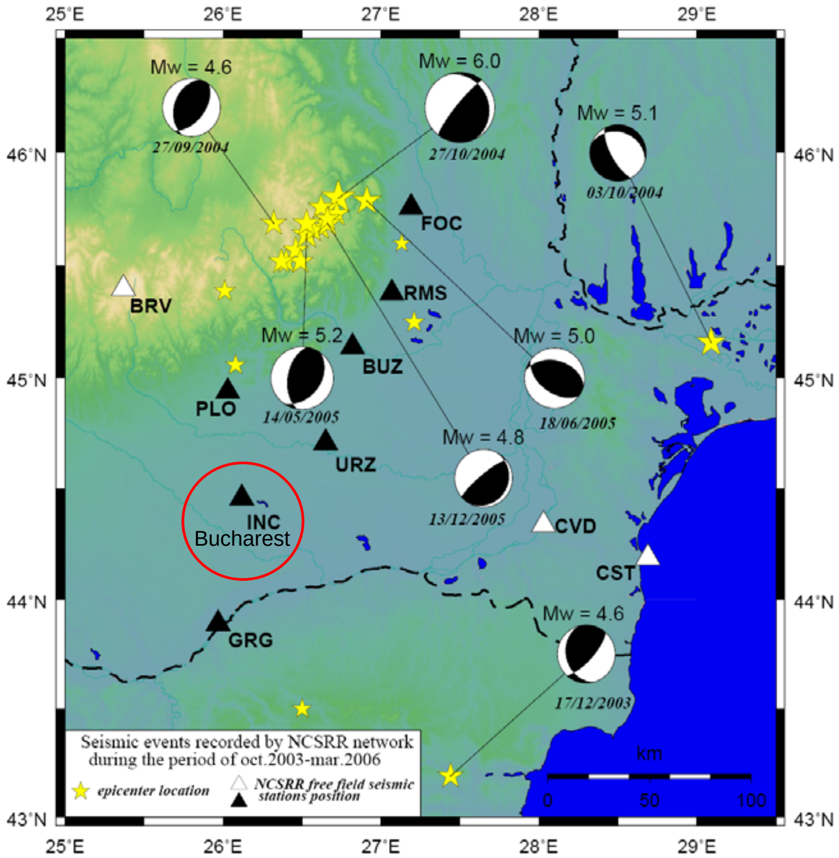

Figure 3. Location of earthquakes recorded by NCSRR stations borehole sites in Bucharest

Table 4. Earthquakes recorded at NCSRR stations with borehole instrumentation in Bucharest

Seismic source	Date	Origin time (UTC)	Coordinates		Depth (km)	Moment magnitude *Mw*
			Lat. (°N)	Long. (°E)		
Vrancea	05/10/2003	21:38:18	45.57	26.46	146	4.6
Bulgaria	17/12/2003	23:15:15	43.19	27.44	60	4.6
Vrancea	21/01/2004	05:49:10	45.6	26.4	118	4.1
	07/02/2004	11:58:22	45.72	26.64	146	4.4
Bulgaria	14/05/2004	11:09:37	43.5	26.5	10	Not reported
Vrancea	10/07/2004	00:34:58	45.52	26.49	150	4.3
	27/09/2004	09:16:23	45.69	26.32	166	4.6
Dobrogea	03/10/2004	09:02:01	45.16	29.09	5	5.1
Vrancea	27/10/2004	20:34:32	45.83	26.77	99	6.0
	17/11/2004	11:31:02	45.74	26.72	127	4.4
	14/05/2005	01:53:22	45.67	26.47	144	5.2
	18/06/2005	15:16:40	45.79	26.91	135	5.0
	05/09/2005	14:23:35	45.76	26.62	90	4.4
	08/09/2005	16:35:50	45.52	26.37	140	4.3
	26/10/2005	22:51:21	45.66	26.57	142	4.3
	13/12/2005	12:14:45	45.78	26.79	144	4.8
	18/12/2005	15:09:43	45.41	26.04	60	3.7
	16/02/2006	02:49:40	45.71	26.66	130	4.1
	06/03/2006	10:40:46	45.69	26.53	145	4.8
	19/03/2006	11:05:53	45.64	26.49	150	4.3
	23/09/2006	05:44:06	45.53	26.43	123	4.2

Table 5. Oct. 27, 2004 Vrancea event - peak accelerations at NCSRR Bucharest stations

Station		UTC1			UTC2			INC			PRC			PRI			SMU		
		NS	EW	V	NS	EW	V	NS	EW	V	NS	EW	V	NS	EW	V	NS	EW	V
Surface	PGA	34.9	58.4	34.4	41.6	40.9	24.8	29.7	29.6	24.9	29.0	49.2	34.0	29.8	79.0	33.1	54.6	44.5	50.8
Shallow sensor	Depth	-28 m			-28 m			-24 m			-28 m			-28 m			-30 m		
	PGA	28.5	14.6	11.1	21.6	16.8	11.5	13.9	12.5	8.3	20.3	13.1	11.2	16.6	37.7	11.8	11.6	18.5	8.2
Deep sensor	Depth	-78 m			-66 m			-153 m			-68 m			-52 m			-70 m		
	PGA	16.5	23.1	9.8	15.6	23.5	7.0	11.3	11.4	6.7	12.7	19.4	8.8	13.2	22.2	9.6	12.6	18.1	8.9

Because a reference nearby rock site is not available in Bucharest area, a non-reference site technique can be used for estimating the site response characteristics: the single station H/V Fourier amplitude spectral ratio. Despite a lack in theoretical justification, the single station spectral ratio was tested successfully for soil sites by an increasing number of authors (Lermo and Chavez-Garcia. 1993, etc.).

H/V spectral ratios at the stations with records during Oct. 27, 2004 event are presented in Figure 4.

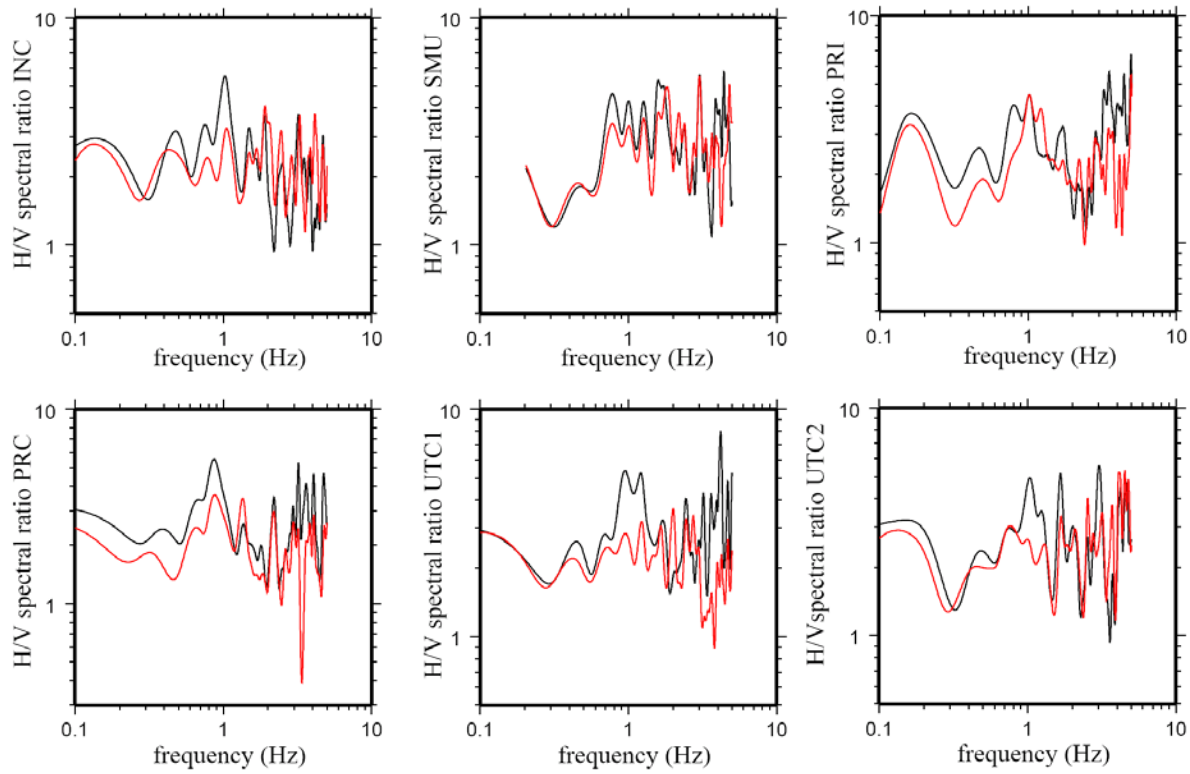

Figure 4. H/V spectral ratios at NCSRR seismic stations in Bucharest (27/10/2004 earthquake)

The H/V ratios in Figure 4 (where the two lines correspond to the H/V ratios of EW and NS components) indicate a ground vibration rather rich in low frequencies, all the ratios displaying significant amplitudes around 1Hz and/or below. A first peak (not of largest amplitude) appears constantly around 0.4-0.5Hz, a second one around 0.7-0.8Hz, and a third one again quite constantly around 1Hz. In a rough approximation, considering a quaternary layer with h=300m thickness and V_S=450m/s shear wave velocity, the vibration frequency $f=V_S/4h$=0.38Hz.

Bonjer *et al.* (1999) indicated a peak of ~0.7Hz all other the city obtained from microtremor measurements, and also reported a 0.5Hz peak using records from May 30, 1990 Vrancea event. It should be noticed that at INCERC site (INC station) a peak at 0.7Hz-0.8Hz was reported by Lungu *et al.*, (1997) using power spectral density H/V ratio for March 4, 1977 earthquake. Also, at INCERC site the same 0.7Hz-0.8Hz peak was obtained from H/V Fourier spectral ratios and H/V displacement response spectra ratios for 1977 earthquake, (Aldea *et al.* 2000). Figure 4 confirms such observations.

The H/V spectral ratio method data accepts the hypothesis that site effects do not significantly affect the vertical component of ground motion. In general, for sites with simple geological configuration, the hypothesis was verified by instrumental data, but in more complex ground conditions a certain influence was noticed in the higher frequency domain, affecting the peak acceleration values. As shown in Table 5, there is a noticeable amplification of peak vertical accelerations from boreholes to the surface. When looking at the recorded data in frequency domain (Fourier amplitude spectra) the vertical motion modification with depth, Figure 5 (example for two seismic stations), it is observed that the differences between spectra appear at frequencies higher than 1.5Hz. The surface motion has stronger high frequency components, explaining the higher peak accelerations observed at surface.

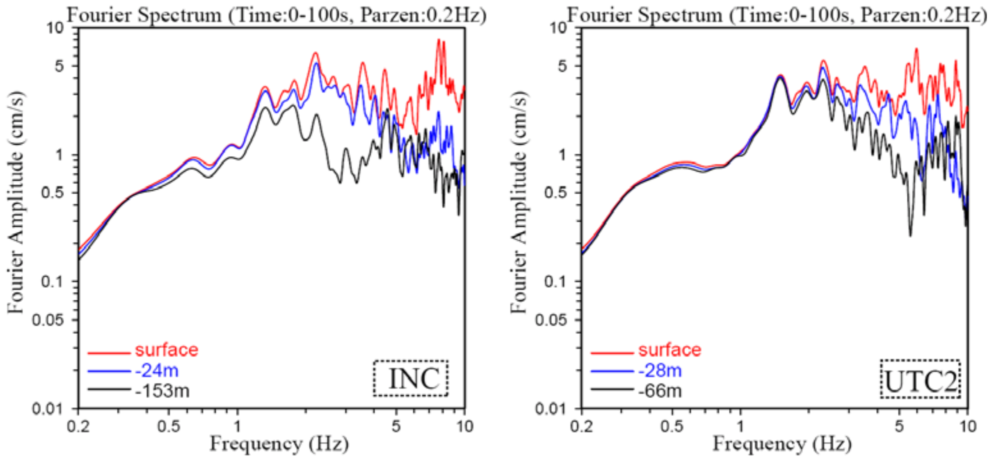

Figure 5. Fourier spectra of vertical ground motion comp. at INCERC & UTC2 (27/10/2004)

Single station microtremor measurements were performed in the summer of 2006 by NCSRR and Tokyo Soil Research Co., Ltd. at 10 sites in Bucharest.

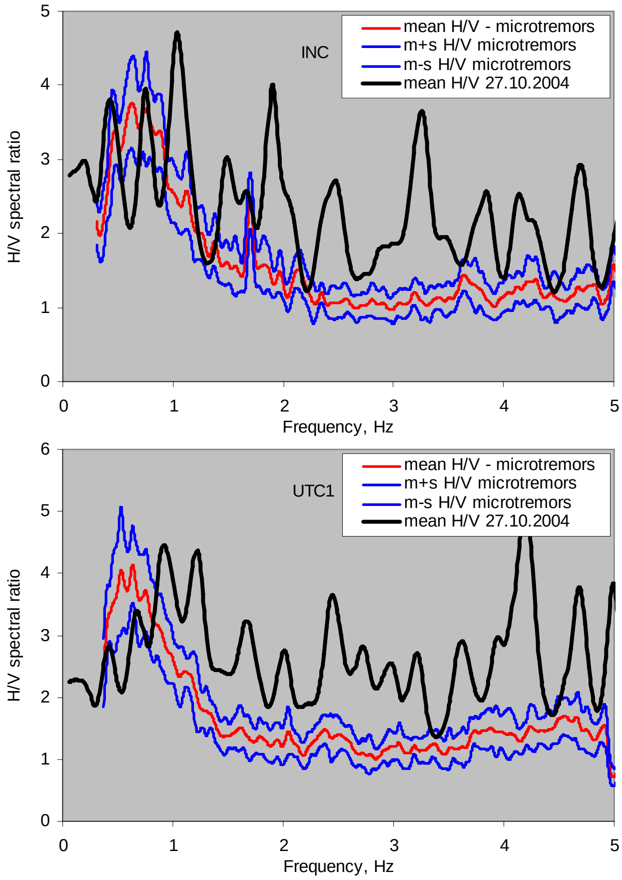

Figure 6. H/V spectral ratios at INC & UTC1 stations (microtremors & 27/10/2004 earthquake)

The H/V spectra from microtremors and earthquake records at two instrumented sites (INC and UTC1) are comparatively presented in Figure 6. In both examples, the H/V from earthquake records is stronger in higher frequencies. Several frequency peaks were captured by both microtremors and earthquake ratios. Low frequency peaks appear in both ratios, indicating a somehow long period of ground vibration due to the thickness of sediments.

The surface/borehole spectral ratio (SBSR) has pro and contra arguments (Atakan, 1998 and Safak, 1997), but it can give a good idea on the response during earthquakes of the soil column between two sensors. Since in our case the deep boreholes are not located on the bedrock, the SBSR does not give a complete image on the site response, but gives useful information on the site response. The surface (S) over deep borehole (B2) spectral ratios for the 27/10/2004 event are presented in Figure 7 (where the two lines indicate the B2/S ratios for EW and NS components). The frequencies corresponding to the first identified peaks in Figure 7 are given in Table 6.

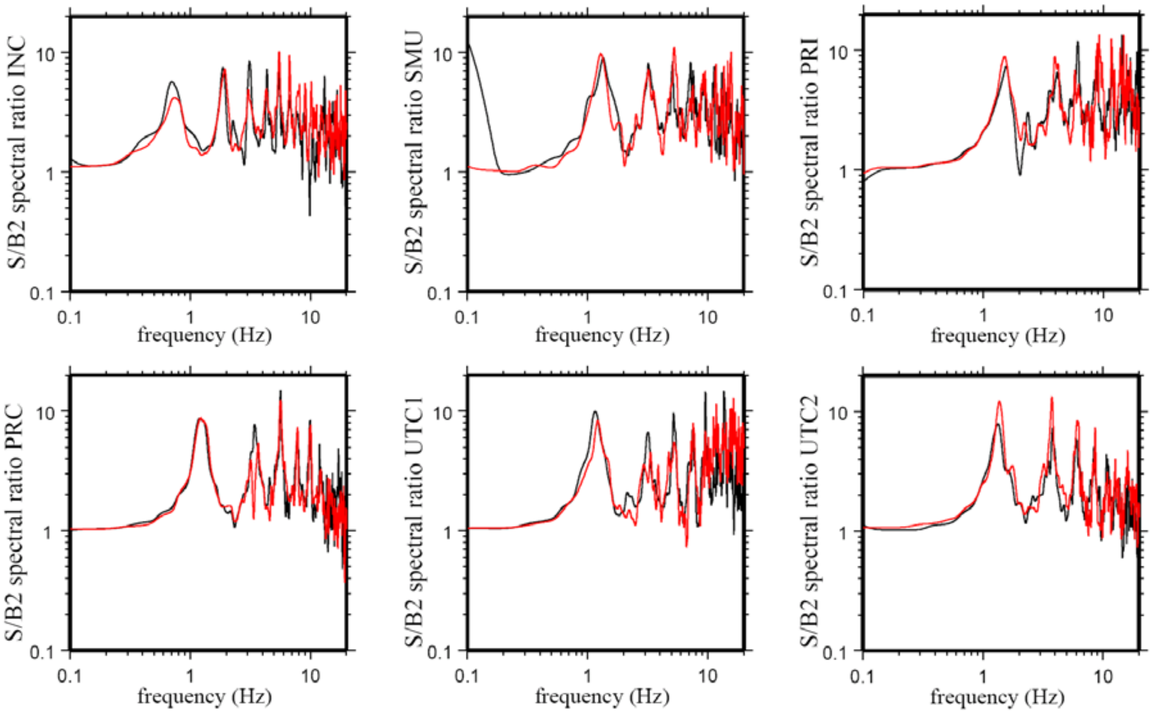

Figure 7. SBSR at NCSRR seismic stations in Bucharest (27/10/2004 earthquake)

Table 6. First frequency peak identified from SBSR (27/10/2004 earthquake)

Station	PRI	UTC2	PRC	SMU	UTC1	INC
B2 borehole depth	-52 m	-66 m	-68 m	-70 m	-78 m	-153 m
SBSR f_1 (Hz)	1.53	1.35	1.21	1.32	1.19	0.7

It can be observed that, in general, deeper the borehole sensor lower the frequency corresponding to the first spectral peak. In case of sites with deep sediments (as it is the case in Bucharest), the site response and the site conditions should be analysed by considering the whole thickness of sediments until the bedrock, and not only the top 30m. INCERC site gives an instrumental proof that the soil category and the design spectrum selected by using only the upper 30 m of soil can be a misleading approach, the strong earthquakes of 1977 (*Mw*=7.5) and 1986 (*Mw*=7.3) having response spectra with large values at long periods, much larger than those from the Eurocode 8 spectra (corresponding to the site category based on the top 30m of soil). The long-period phenomenon was explained by the contribution of two factors: the source characteristics in case of strong Vrancea events and the site conditions (thick sediments with probably non-linear behaviour during strong earthquakes). Even the SBSR presented in Figure 4 are characterising the soil column response between the two sensors and in elastic range, they show that the soil thickness has an important contribution in the site response.

SITE RESPONSE USING MULTIPLE EARTHQUAKE RECORDS

At UTC2 station (Technical University of Civil Engineering Bucharest, Campus in Pache Protopopescu Street) in central Bucharest were recorded 15 earthquakes. The average amplification of peak horizontal ground motion due to the upper 28 m of soil was 2.1, and the one from -66m to surface was 2.3, so the top soil was the major contributor to the *PGA* amplification.

At INCERC station (Pantelimon Street) in Eastern Bucharest were recorded 11 earthquakes. The average amplification of peak horizontal ground motion due to the upper 24 m of soil was 2.2, and the one from -153m to surface was 2.7, so the top soil is still the major contributor in terms of *PGA* amplification. However from -153m to -24m there is also an increase with 30% in average.

For the two sites, in Figure 8 are presented the surface over deep borehole spectral ratios in two cases: the average of EW and NS components ratios for the record obtained during the strong earthquake of 27/10/2004 (*Mw*=6), and the average of EW and NS components ratios for all the other records obtained during the small earthquakes described in Table 3, except the (*Mw*=6) one. As expected, since in case of the records from the strong *Mw*=6 earthquake the ground shaking had low amplitudes in Bucharest (in general bellow 50cm/s^2), nonlinear soil behaviour did not appear, and the spectral ratios are almost similar with a stable position of the peaks.

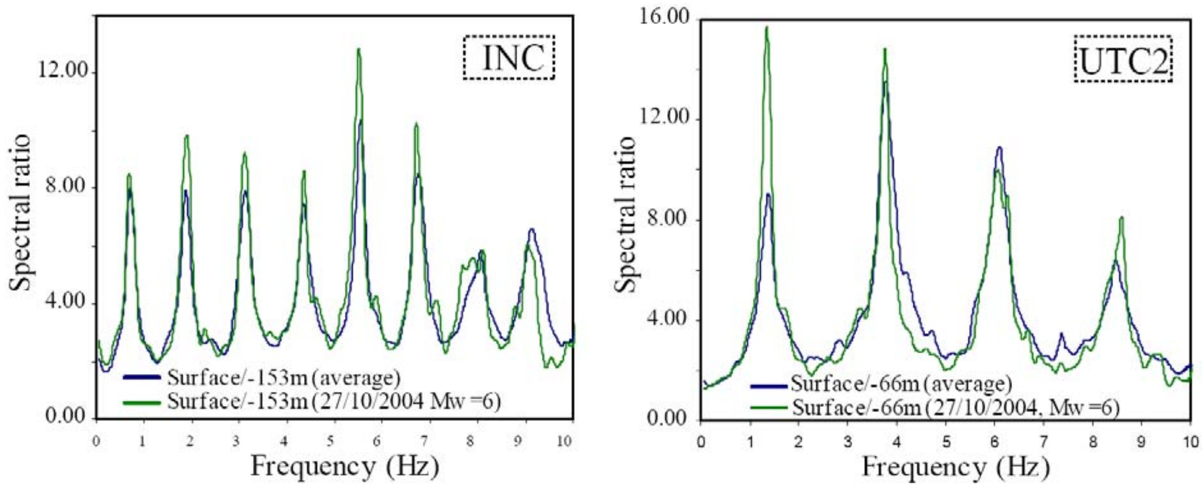

Figure 8. SBSR at INCERC (left) & UTC2 (right) sites (small vs strong earthquakes)

In Figure 9 is presented a comparison of the SBSR from surface to the shallow borehole sensor and from the shallow borehole sensor to the deep one for the seven stations in Bucharest, the ratios being the average of ratios of all the horizontal components form all recorded earthquakes.

It can be observed that the top 24÷30 m of soil does not influence the position of peak frequencies in the spectral ratios, the peaks having a good stability. At all sites the first peak appeared around 1Hz, as it was the case during the October 27, 2004 event (Figure 7), and the depth of the deep borehole controls the position of the first peak. The data shows that even during small earthquakes the ground vibration in Bucharest has low frequency (long period) components. The spectral ratios between the shallow borehole and the deep borehole also captured nicely the frequency characteristics of ground response, but the amplitudes are in general significantly reduced at frequencies higher than ~1.5Hz.
The site response in the low frequency domain is governed by the deep layers, while the the upper soil contribute significantly in the high frequency domain, increasing the peak values of acceleration. At several sites (VIC, UTC1, PRI, SMU) there are large amplitudes of the spectral ratios in the high frequency domain, indicating that some local anthropogenic sources are influencing the records, VIC being the most critical site from this point of view.

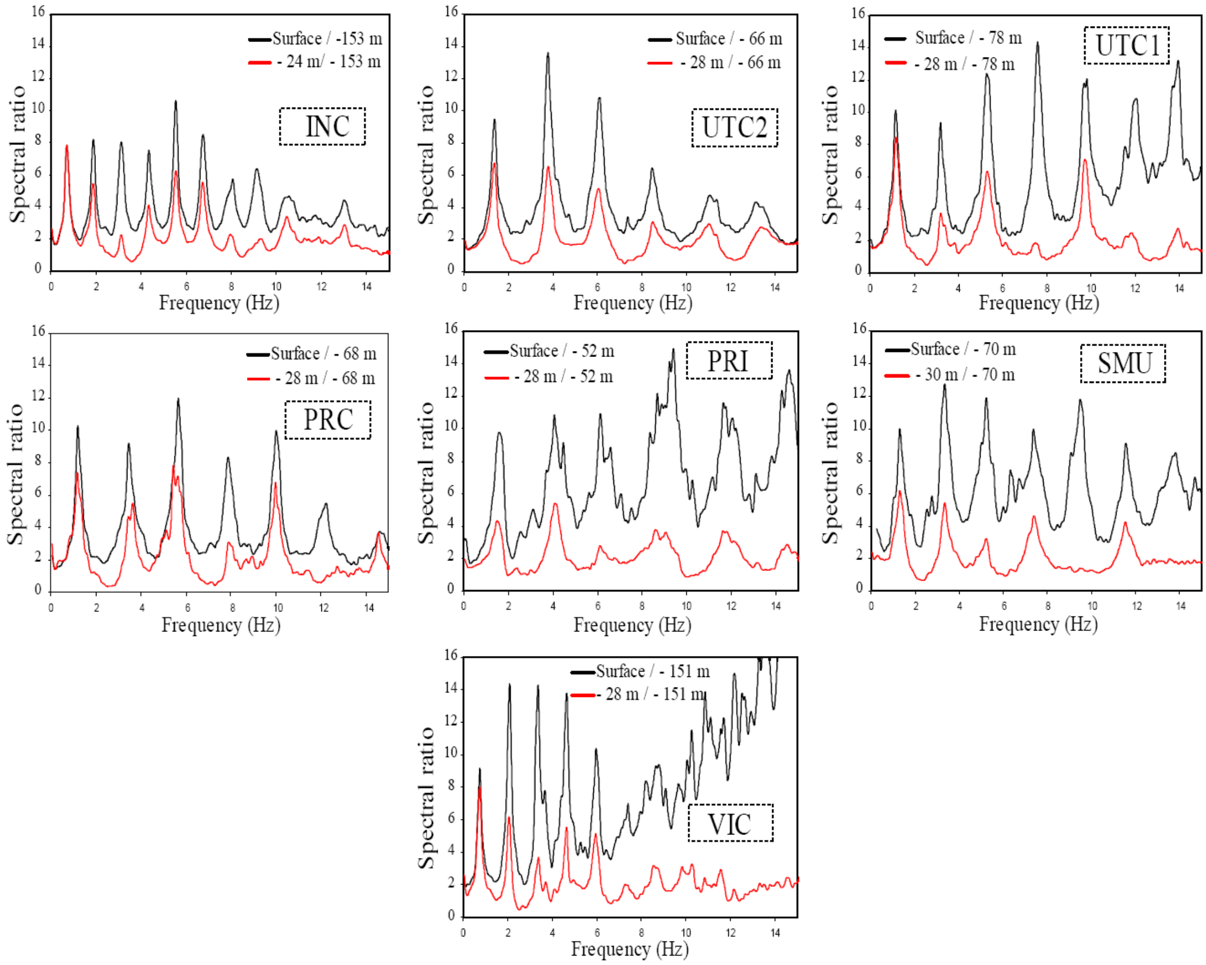

Figure 9. Average SBSR at NCSRR borehole sites in Bucharest

The H/V and SBSR methods have to be applied, compared and discussed for all sites and all records. Analytical site response studies should be performed in order to construct and validate appropriate ground models that incorporate results from down-hole tests and from array microtremor measurements. Comparisons have to be done with earthquake data from past strong Vrancea earthquakes (March 4, 1977, August 30, 1986 and May 30/31, 1990).

CONCLUSIONS

The National Center for Seismic Risk Reduction seismic network (installed with support from JICA) allows the observation of site response in a dense array in the central and northern half of Bucharest, with sensors at ground surface and in boreholes. The seismic activity of Vrancea subcrustal source, as well as of shallow sources in Romania and Bulgaria offered 63 records in 3 years, generally from small earthquakes, but a moment magnitude 6 event was also recorded. The extrapolation of results from small to large earthquakes ($Mw \geq 7$) is difficult, especially due to the different source characteristics and to the possible non-linear soil behaviour. However, the available and the future data may help to identify characteristics of site response in Bucharest and to calibrate appropriate ground models for analytical studies. All efforts and results related to an improved definition of seismic input in Bucharest are helpful for the mitigation of the "big one" (an earthquake that can be similar or even larger than the March 4, 1977 earthquake that, unfortunately, should not be considered as a worst possible case). The earthquake records are fundamental for understanding the site and building response during earthquakes, and for improving the earthquake resistant-design regulations, consequently the new NCSRR seismic network is an important achievement for these purposes.

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