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Extensive seismic instrumentation and geophysical investigations for site-response studies in Bucharest, Romania

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ABSTRACT - In the frame of the *Japan International Cooperation Agency (JICA*) seismic risk reduction Project in Romania (2002-2007, Ref.#7241011E0), the *National Center for Seismic Risk Reduction (NCSRR*, Bucharest) instrumented in 2003 seven sites in the northern half of the capital city Bucharest. The instrumentation at each site consists of three triaxial acceleration sensors: one at ground surface and two in boreholes - one shallow borehole (around 30m depth) and one deep borehole (with depths ranging from 50m to 153m). Recently another site was instrumented by Romanian efforts (triaxial sensors at free-field and in a 30m depth borehole). *NCSRR* performed down-hole measurements at all the 8 sites that were later instrumented, the deepest investigation going down to -140m depth. Also *NCSRR* performed array microtremor measurements at three sites in the northern half of Bucharest using small, medium and large size arrays, with station-to-station distances up to about 3.5 km. The obtained phase-velocities were inverted by a genetic-algorithm methodology (Yamanaka and Ishida, 1996). The *NCSRR* seismic network already recorded 60 ground motions from 19 earthquakes with moment magnitudes ranging between 3.7 and 6.

1. Introduction

The seismic hazard in Bucharest City, the capital of Romania, is dominated by the contribution of Vrancea intermediate depth (60-170km) subcrustal seismic source, located at about 100-150km north-east. Ground motions from shallow seismic sources from Romania and Bulgaria are also felt or recorded in Bucharest, but have negligible effects.

At north of Danube the Moesian Platform is called “Romanian Plain” and Bucharest is located in it's central part. The Cretacic basement was identified at about 1000÷1500m depth and is covered by Sarmatian and Pliocene deposits. Before Pliocene the whole area between Carpathian Mountains and Danube was a sea. The sea gradually disappeared and heterogeneous Tertiary and Quaternary deposits of sediments are composing the Romanian Plain. The Tertiary formations in Bucharest area are estimated to be about 700-800m thick, and they are covered by Quaternary sediments (about 200 m in the south, and 300 m in the north) consisting mainly of gravel, sands and clays.

During the strong March 4, 1977 Vrancea subcrustal earthquake (moment magnitude Mw=7.4-7.5, focal depth h=109km) a peculiar ground motion was recorded in Bucharest.

"It is indeed fortunate that at least one reliable observation of the ground motion was made in Bucharest. It appears to be a very interesting one which may modify the concepts of standard response spectra." (EERI, 1977). The motion displayed a powerful pulse with long period (~1.4s), and the acceleration response spectra had important amplifications between 1s and 2s, together with the Mexico City SCT 1985 record becoming a kind of benchmark for earthquake engineering studies related to long period motions.

On August 30, 1986 another strong Vrancea event (Mw=7.2-7.3, h=133km) came to confirm the special characteristics of strong ground motion in Bucharest. This time several records were obtained within the city, all of them displaying significant spectral amplifications beyond 1s (Aldea *et al.,* 2004). The records also showed the variability of site response within the city in terms of peak values of ground motion and of frequency content indicators (Lungu *et al*., 1997, Aldea, 2002).

On May 30, 1990 a moderate Vrancea event (Mw=6.9-7.0, h=91km) was recorded in Bucharest, indicating that the narrow frequency content and the amplifications of response spectra beyond 1s are disappearing for moderate events (Lungu *et al*.,1997). Records from small earthquakes in the recent years also confirmed this observation.

Several studies for the microzonation of Bucharest were made in the past: 1953, 1964, 1972, and 1974. These studies were based on geologic and geotechnic data and provided microzonation maps for seismic intensity. The strong 1977 earthquake was a natural test for the microzoning maps. None of these maps matched the pattern of destruction in Bucharest due to 1977 earthquake: "The city of Bucharest was microzoned for seismic risk in 1974 as a part of a UNESCO project - Survey of Seismicity of the Balkan Region. The region of greatest destruction lies mainly in the microzone designated as least vulnerable." (Berg, 1977). In the 90's the efforts toward the seismic microzonation and the understanding of site response were continued at *Technical University of Civil Engineering Bucharest (UTCB)*, with support from Bucharest City Hall, Ministry of Research and *French Association for Earthquake Engineering AFPS* (Lungu *et al*., 1997 & 1999). These studies used the available database of ground motions and ground data, improved the regional seismic hazard assessment and used Geographic Information Systems GIS for microzoning the ground motion characteristics during past earthquakes. The available data was not sufficient for the complete understanding of site response within the city and for the construction of predictive microzonation maps.

The high seismic risk of Bucharest City is forcing the scientific and technical community to continue the efforts toward site response understanding and modelling.

Such special ground motions as the Bucharest 1977 record are explained by a combination of source effects and site effects. Studies on the Vrancea source and on the site effects in Bucharest became of interest for national and international efforts/projects.

The present paper presents recent developments done with Japanese support.

2. The seismic risk reduction Project of JICA in Romania

In 1998, at the initiative of researchers from *UTCB* started negotiations with *Japan International Cooperation Agency (JICA*) for the construction of an earthquake-related project in Romania. In 2002 the Project "Seismic risk reduction for buildings and structures" was signed, and the *National Center for Seismic Risk Reduction* (*NCSRR*, Bucharest) was created under the authority of Ministry of Transports, Construction and Tourism, in order to implement it. Between the several activities and objectives of the Project and of *NCSRR* (Vacareanu and Kaminosono, 2006), an important support was given to the seismic instrumentation and to the geophysical investigations. The Romanian Ministry also supported this direction by investing in seismic instrumentation.

2.1. The NCSRR seismic network for site-response assessment

The *NCSRR* seismic network (Aldea *et al*., 2004, 2006) contains free-field, building, and free-field & boreholes instrumentation. *NCSRR* installed in 2003 in Bucharest 7 Kinemetrics stations (donated by *JICA)* with sensors at ground surface (generally in free-field conditions) and in boreholes at two levels of depth: at ~30m depth and between 52m and 153m depth (Fig.1, Table I). In 2005 another site was instrumented with Geosig equipment (free-field & a 30m depth borehole) with Romanian financial efforts.

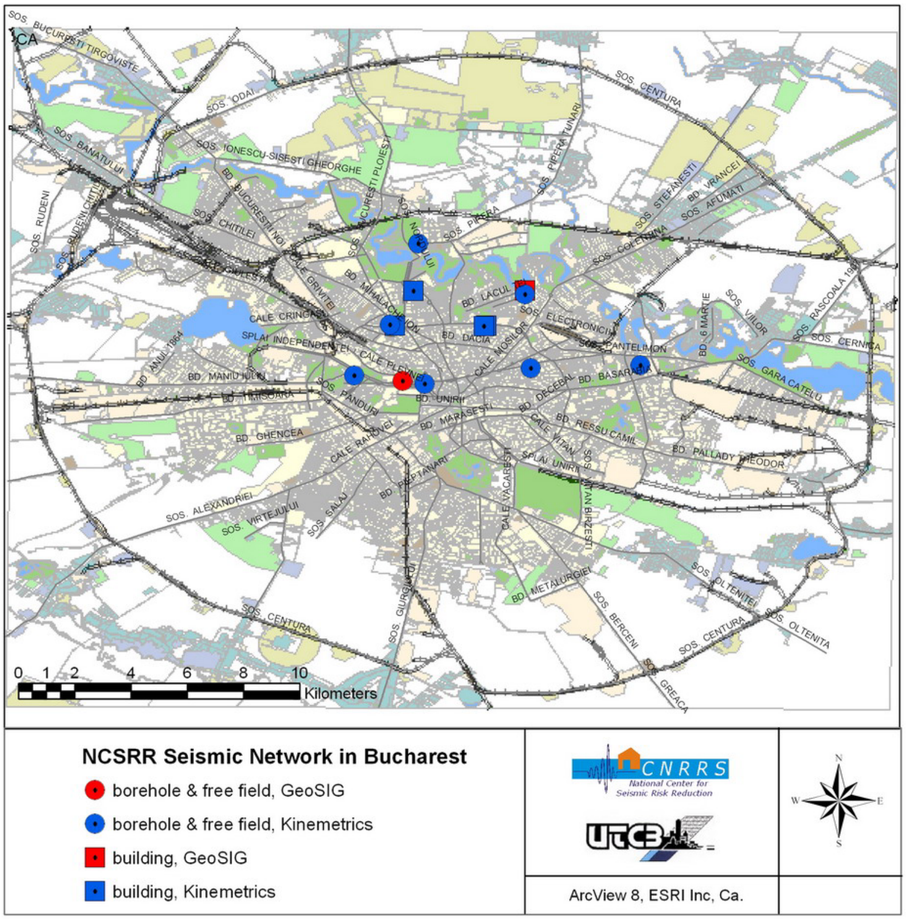

Figure 1. NCSRR seismic network in Bucharest

Table I. *NCSRR* free-field & borehole seismic stations in Bucharest

Site	Id	Surface sensor location	Depth (m) of sensor in shallow borehole	Depth (m) of sensor in deep borehole	Type of equipment
UTCB Tei	UTC1	free field	-28	-78	Kinemetrics K2 +FBA-23DH
UTCB Pache	UTC2	1 storey bldg.	-28	-66	
NCSRR/INCERC	INC	1 storey bldg.	-24	-153	
Civil Protection	PRC	1 storey bldg.	-28	-68	
Piata Victoriei	VIC	free field	-28	-151	
City Hall	PRI	free field	-28	-52	
Municipal Hospital	SMU	free field	-30	-70	
UTCB Plevnei	UTC3	free field	-30		Geosig GSR24 +AC23DH

2.2. Ground conditions at NCSRR seismic stations sites

At all the *NCSRR* seismic stations the soil profile/stratigraphy of the boreholes is known, and *NCSRR* and *Tokyo Soil Research* performed in 2003 down-hole tests for the estimation of S & P velocities profiles. In Table II are presented the S velocity profiles and the average (*UBC 97* formula) shear wave velocity (Vs) for the sites instrumented with Kinemetrics equipment, using the upper 30m, the upper 52 m and the whole investigated soil profile, and their approximate corresponding predominant periods (4Σh/average Vs).

Table II: Average shear wave velocity at NCSRR stations based on down-hole tests

Station	City Hall		Municipal Hospital		NCSRR/ INCERC		Piata Victoriei		UTCB Pache		Civil Protection		UTCB Tei	
h (m) / Vs (m/s)	h	Vs	h	Vs	h	Vs	h	Vs	h	Vs	h	Vs	h	Vs
Velocity profile	9	140	2	150	5.5	260	3	180	0.3	130	4	190	4.5	270
	17	280	11	210	1.5	260	7	280	1.7	130	8	290	6.2	270
	14.3	340	20.5	300	12	260	14	300	2	330	4	350	5.3	380
	11.7	380	13.5	350	9.5	280	15	350	5	330	27	330	8	310
			22	400	7	350	11	350	5	240	8	340	20	340
					7.5	350	9	390	11	330	17	380	4	340
					12	380	12	370	30	370			14.4	430
					19	380	19	420	11	410			15.6	390
					20	400	14	420						
					20	440	6	420						
					21	440								
					5	440								
Investigated depth, m	52		69		140		110		66		68		78	
Average (30m) *Vs*, m/s	219		245		270		284		288		293		309	
Predominant period (30m), s	0.55		0.49		0.45		0.42		0.42		0.41		0.39	
Average (52m) *Vs*, m/s	258		281		302		310		318		309		326	
Predominant period (52m), s	0.81		0.74		0.69		0.67		0.65		0.67		0.64	
Average *Vs*, m/s (whole borehole depth, m)	258 (52)		303 (69)		364 (140)		354 (110)		332 (66)		324 (68)		349 (78)	
Pred. period (whole depth), s	0.81		0.91		1.54		1.24		0.79		0.84		0.89	

One can observe that the differences between the sites are not very important, after some somehow weaker top layers follow layers with velocities in the range 300-400m/s, and the bedrock is not reached at any of the sites. In all cases of averaging, 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 *EC 8*.

In the above mentioned codes, these ground classes are associated with a control period of response spectra Tc of 0.6s, which is not in agreement with the real situation in Bucharest, where during August 30, 1986 Vrancea earthquake the values of Tc were higher than 0.6s all over the city (Lungu *et al*, 1997, Aldea, 2002). In the future editions of earthquake resistant design code, the ground categories should also maybe be related to the predominant period of the site, and not only to the characteristics of the upper 30m of soil profile, since the important thickness of medium-to-hard sediments can also induce long periods motions with high spectral amplifications beyond 1second. The influence of soil thickness on the predominant periods in Table II is self-explanatory.

2.3. Array microtremor investigations

The array microtremor technique was used within the *JICA* project (Aldea *et al*., 2006), focusing on the deep geology of Bucharest and on the identification of the main layers corresponding to significant changes of velocity. Three sites were investigated by the use of array microtremor measurements (Figure 2): INCERC in eastern Bucharest, EREN in north-western Bucharest and Civil Protection (PRC) in northern Bucharest. At all the sites stratigraphy data are available and down-hole tests were previously performed.

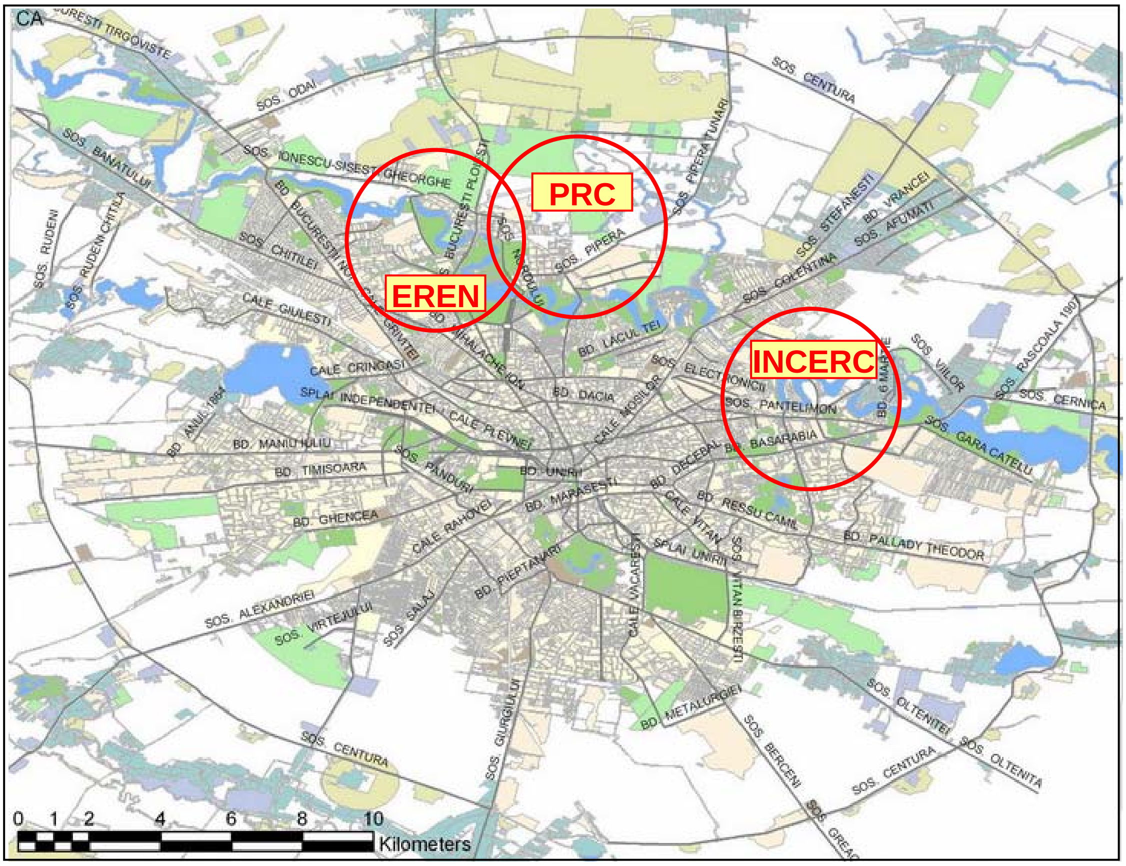

Figure 2. Location of the arrays for microtremor observation in Bucharest

A first set of measurements were performed in 2004 in cooperation with *Tokyo Soil Research*: medium size array at INCERC site, and small, medium and large size arrays at EREN. The disposal of sensors was according to the requirements of spatial autocorrelation method (SPAC): a circular array consisting of 4 stations, arranged in the shape of an equilateral triangle shape and its center. The radius of array at INCERC was of ~150m, and at EREN ~10m, ~38m, ~150m and ~600m.

In 2005 a second set of measurements was performed in cooperation with *Tokyo Institute of Technology*: a large size array at INCERC site and medium and large size arrays at PRC site. Each array was composed by 7 observation points, disposed in a somehow triangular shape and in the center of the triangle, for applying the frequency-wavenumber (F-K) method. The largest distance between two points was of ~2km for the INCERC large size array, of ~1.2km for the PRC medium size array and ~3.5km for the PRC large size array.

In Figure 3 are comparatively presented the phase velocity dispersion curves for the three sites sites, as selected for being used in the inversion procedure.

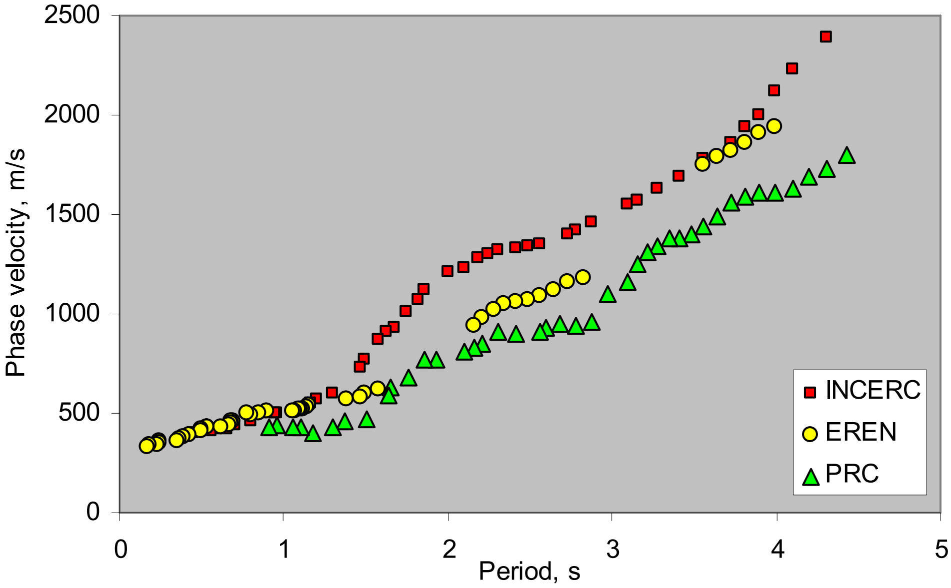

Figure 3. Selected observed phase velocities at INCERC, EREN and PRC sites

The inversion of phase velocities was done using the Genetic Algorithms (GA) procedure, adapted for this purpose by Yamanaka and Ishida (1996) as a powerful global optimisation method. The Genetic Algorithms consist of selection, crossover and mutation of individuals in a population. In order to facilitate the convergence to an optimal solution, an elite selection was added for ensuring that the "best" individual with the smallest misfit values is not excluded from the succeeding generation, together with a dynamic mutation which contains a generation-variant mutation probability (Yamanaka and Ishida, 1996).

The genetic inversion has been successfully applied in inversion of phase velocity from microtremor array exploration. Details can be seen in Yamanaka *et al*. (2000).

In Fig.4 are presented the plus one & minus one standard deviations for each phase velocity selected for inversion at PRC, and with continuous line is represented the theoretical phase dispersion computed from the velocity profile obtained by inversion. Computations were performed with software developed at *Tokyo Institute of Technology*.

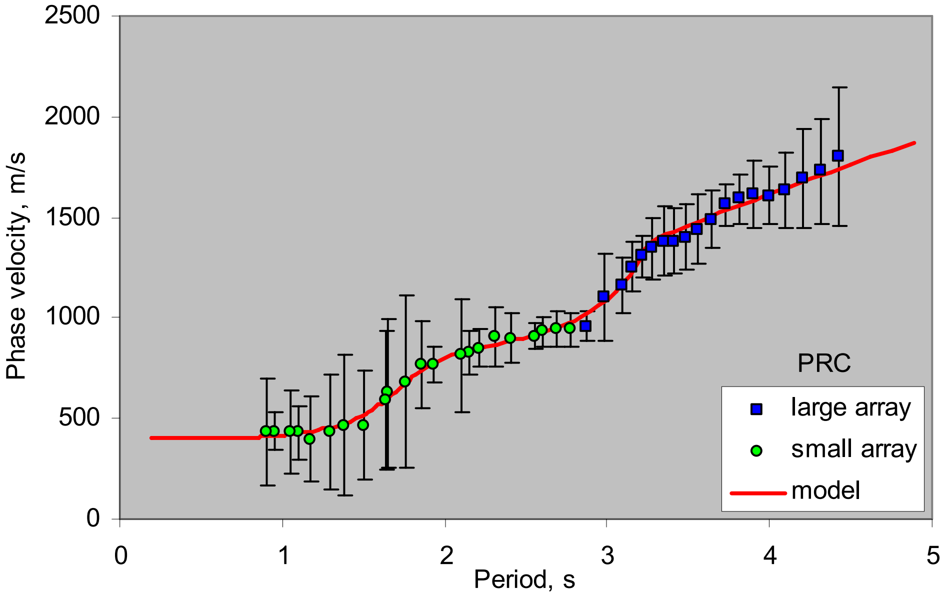

Figure 4. Observed versus theoretical phase velocities at PRC site

The layer model for inversion was selected in a simple form, i.e., 3 macro-layers over the bedrock, in order to identify the significant changes of velocity. The share wave velocity of the seismic bedrock was assumed to be around 3000m/s, thus the search limits for this layer were constrained between 2900m/s and 3100m/s. For the 3 soil layers the share wave velocity and thickness were set free. In Table III are presented the inversion results.

Table III. Share wave velocity (Vs) and thickness (h) obtained by GA-based inversion of microtremor phase-velocities

	INCERC		EREN		PRC	
	Vs (m/s)	h (m)	Vs (m/s)	h (m)	Vs (m/s)	h (m)
Layer 1	455	268	474	358	421	323
Layer 2	917	449	1146	985	949	1141
Layer 3	1493	979	1693	650	2413	380
Seismic bedrock	2948	∞	2977	∞	3032	∞

These results are considered as preliminary, since further microtremor array measurements and consideration of down-hole measured velocities of the surface geology will be integrated in future work.

2.4. Earthquake records from NCSRR network

The *NCSRR* seismic network recorded until now over 130 motions from 22 earthquakes. The network component devoted to the site response assessment in Bucharest gathered 60 records distributed according to the seismic source as presented in Table IV. On October 27, 2004 a strong earthquake (Mw=6.0, h=99km) occurred in Vrancea region. It is the strongest earthquake recorded by *NCSRR* seismic network. It should be underlined that all the records characterise the ground motion in elastic behaviour, even in the case of the strongest event recorded.

Table IV. Distribution of seismic records at *NCSRR* stations for site response investigation in Bucharest

Earthquake source	No. of recorded earthquakes	No. of records
Vrancea subcrustal	16	54
Bulgaria shallow	2	5
North Dobrogea shallow	1	1
Total	19	60

As an example, in Figure 5 is presented the record from NCSRR/INCERC station during the Oct.27, 2004 event. The evolution with depth of acceleration response spectra and Fourier amplitude spectra are given in Figure 6, for the same seismic event.

This example, as well as all the borehole records in general, presented some characteristics. In terms of peak ground acceleration there is a negligible difference between the values in the deep borehole and the values in the shallow borehole, and there is a significant amplification from the shallow borehole to the surface, between 2 to 3 times. The amplification of PGA due to the top ~30m of soil was proved to be have the major contribution for the surface ground motion PGA. The same aspect was observed for the acceleration response spectra: the spectra in boreholes are somehow similar, while the spectra at surface are amplified.

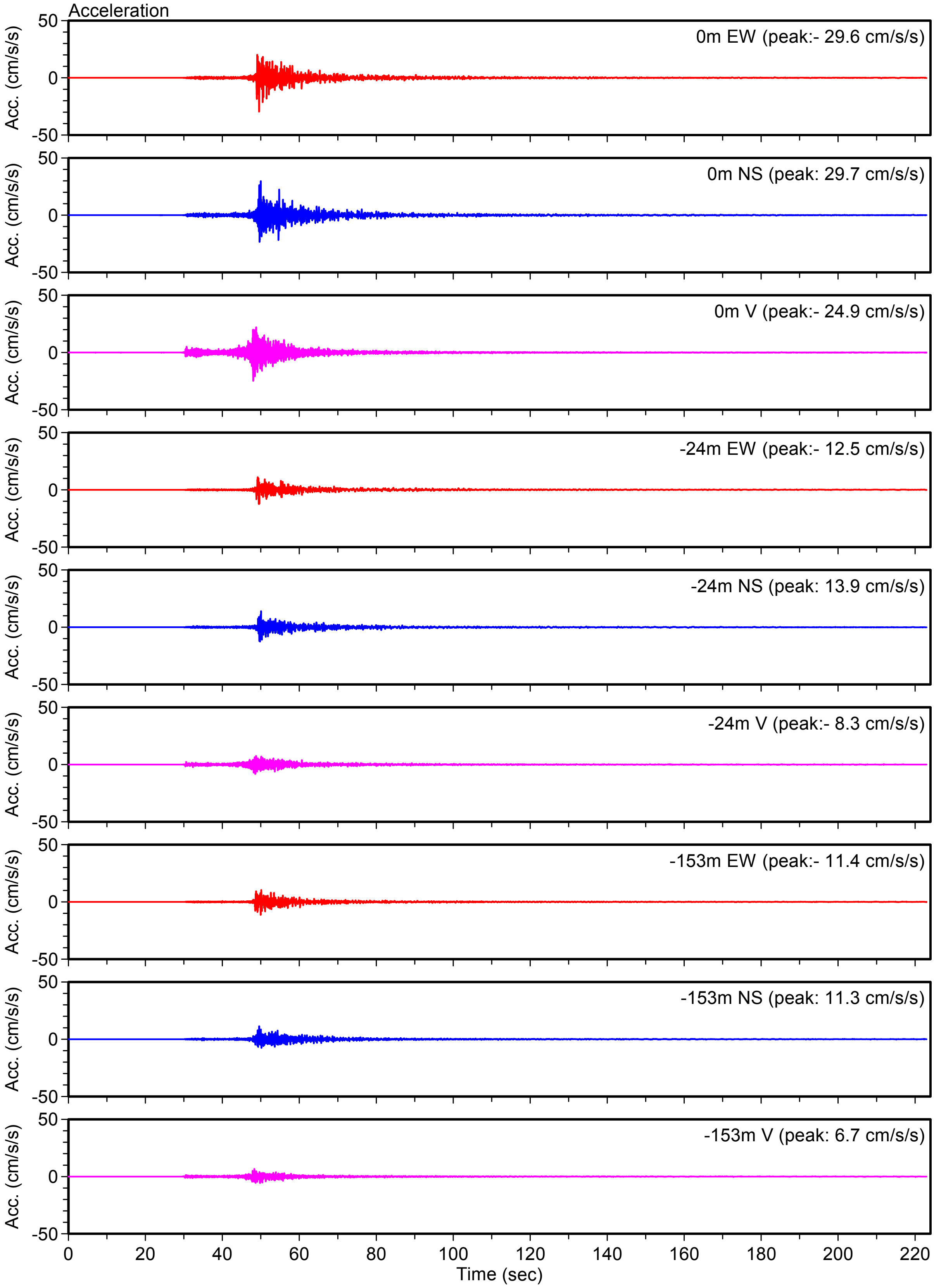

Figure 5. Evolution of acceleration time histories with depth at NCSRR/INCERC site

It will be important and interesting to analyse in the future strong ground motions that include the non-linear effects, and to check the amplification of response spectra in the long period range and, eventually the saturation of peak ground acceleration.

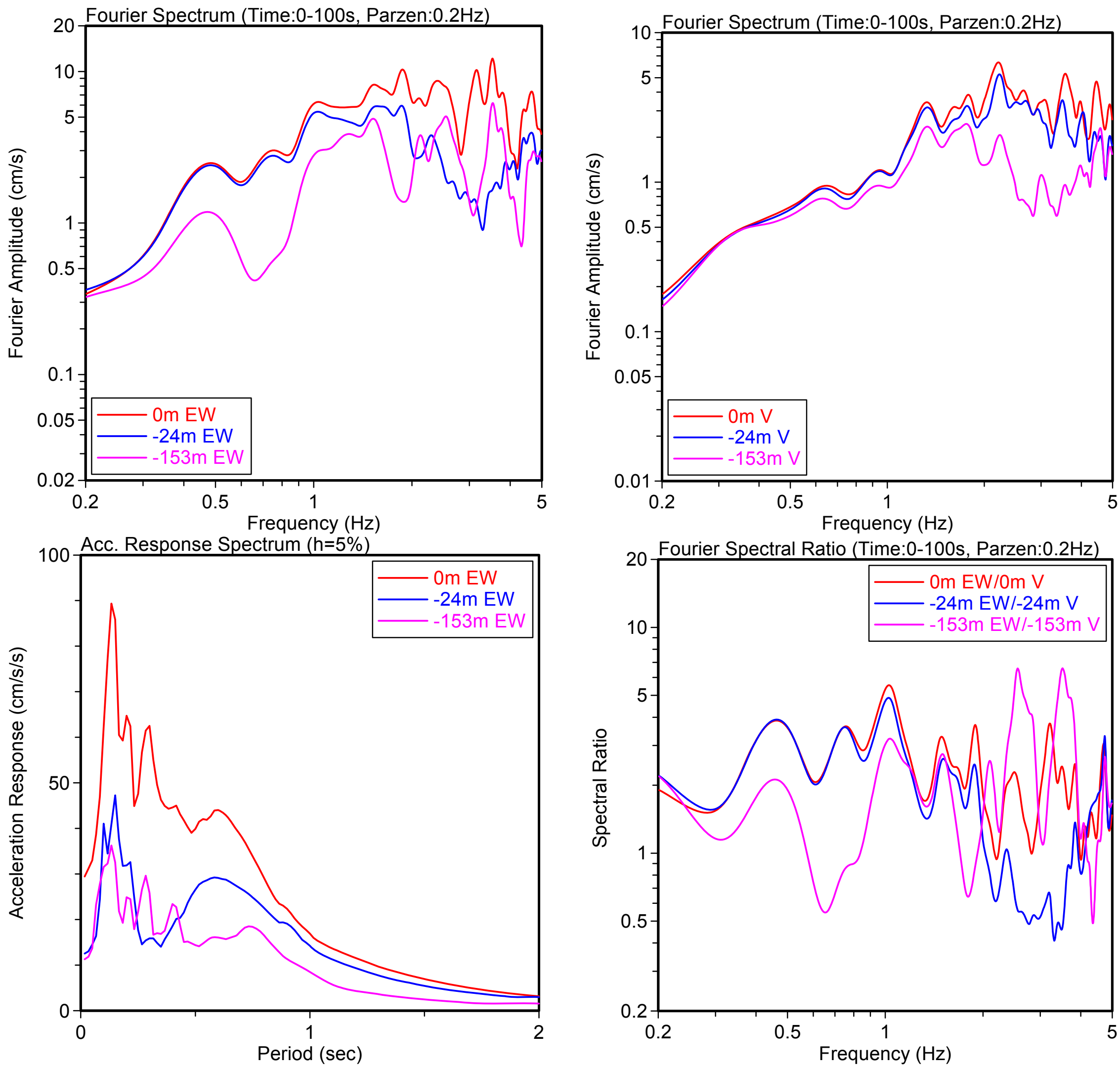

Figure 6. NCSRR/INCERC site. Evolution of Fourier spectra, acceleration response spectra and H/V spectral ratio with depth (Oct.27, 2004 Vrancea earthquake)

At low frequencies the Fourier spectra for horizontal components are almost identical at surface and in the shallow borehole, differences appearing beyond 1Hz. The Fourier spectra for horizontal components in the deep borehole are clearly smaller at low frequencies and become similar to the ones in the shallow borehole at higher frequencies. The H/V spectral ratio technique accepts the hypothesis that site effects do not affect the vertical component of ground motion. In general, for sites with simple geological configuration, the hypothesis was instrumentally verified, but in more complex situations a certain influence was noticed, the differences being reported at high frequencies. Fig.6 confirms these ideas, the vertical Fourier spectra being almost identical at low frequencies. The H/V spectral ratios in Fig.6 indicate that ratios at surface and in the shallow borehole are practically identical up to 2 Hz, so the top soil layers do not influence much the main vibration modes. The shape of H/V spectrum in the deep borehole displays a clear peak at about 0.5Hz, which may be an indication that there is still a certain thickness of sediments until the bedrock and that this low frequency peak is due to the deeper geology. In general, the H/V spectra at *NCSRR* stations do not indicate medium/hard soil conditions, all the ratios displaying significant amplitudes in the low frequency range. A first peak (not of largest amplitude) appears constantly at 0.4-0.5Hz, a second one around 0.7-0.8Hz, and a third one again quite constantly around 1Hz.

3. Conclusions

The *NCSRR* dense seismic network in Bucharest provides an interesting test site for the investigation of site response, with 15 instrumented boreholes up to a maximum depth of 153m. The analysis of earthquake records should be supplemented with numerical modelling studies based on the available borehole data, measured seismic waves velocities and results from array microtremor observations. A special attention should be considered in the extrapolation of results from small amplitude vibrations (i.e., elastic soil behaviour) to strong ground motion modelling, in the absence of such recorded motions.

4. Acknowledgements

Authors would like to acknowledge *Japan International Cooperation Agency* not only for the seismic instrumentation installed within the seismic risk reduction project, but also for the continuous support that also included working periods of Romanians in Japan and of Japanese in Romania. Authors also want to acknowledge the support of staff from *NCSRR*, *BRI*-Japan, *UTCB*, *INCERC*, *MTCT*, and all institutions hosting seismic stations.

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