Site response assessment using ambient vibrations and borehole-seismic records

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SUMMARY:
The paper presents a site response analysis based on seismic records, ambient vibrations and numerical modelling (equivalent linear approach). At the site (located in Bucharest, Romania) a seismic station recorded between 2003 and 2010 ground motions during 15 earthquakes with moment magnitudes ranging from 4.1 to 6 (14 from Vrancea subcrustal source with focal depths between 60km and 166km, and 1 from Shabla source in the Black Sea, with 10 km focal depth). Surface-over-borehole spectral ratios, H/V spectral ratios, spectral analysis and analytical results are compared and discussed and references to the seismic design codes provisions (Eurocode 8, Romanian P100-1/2006 code, etc.) are given. The relevance of using the upper 30m of soil deposits for defining seismic action for design is also addressed, together with a discussion on the characteristics of ground motion at surface and at -28m and -78m depth.

Keywords: site response, seismic records, ambient vibrations, equivalent linear analysis

1. INTRODUCTION

Despite it's moderate seismic activity, Romania is associated with one of the highest seismic risk in Europe, due to the strong earthquakes originating from the intermediate depth Vrancea source. The first Romanian strong ground motion recorded in Bucharest at INCERC station during the destructive 1977 earthquake (moment magnitude Mw=7.4÷7.5, focal depth h=109 km) attracted international attention due to it's characteristics: "The field study of the Romanian earthquake of 1977 suggests that strong ground motions, for engineering purposes, may differ considerably from those currently adopted for design on the basis of US West Coast-type of recordings." (Ambraseys, 1977); "This accelerogram is so different from those obtained from other destructive earthquakes that one is at first tempted to say something must be wrong with the record. Chris Rojahn inspected the instrument and says it was properly installed and maintained, and he sees no reason to doubt the record." (Berg et al., 1980); "The record, unlike most obtained from other de-structive earthquakes, is characterised by a single strong pulse with a period of about 1.4 seconds. It's spectrum intensity exceeds that of the 1940 El Centro earthquake, which has long served as some-thing of a benchmark for strong ground motion." (Fattal et al., 1977).

The long predominant period (1.3-1.5 s) of ground vibration in Bucharest was repeatedly underlined (Lungu et al., 1997, 2000, Aldea et al., 2003, 2009, etc.), especially for sites located in central and eastern Bucharest. The recorded motions from the 1986 and 1990 Vrancea earthquakes showed that only the strong (Mw>7) seismic events reveal the evidence of the long period (over 1 second) of ground vibration in Bucharest. There is a significant mobility of the frequency content with magnitude (Lungu et al., 1997): smaller the earthquake magnitude larger the frequency band of recorded motions, and larger the magnitude, narrower the frequency content. The explanation comes from the combination of source mechanisms during strong and moderate Vrancea earthquakes with the Bucharest ground conditions (deep sediments).

The paper presents the site response assessment at the site of a seismic station (UTC1) located in Northern Bucharest, at Technical University of Civil Engineering Bucharest (UTCB).

1.1. Available recorded data

The UTC1 seismic station was installed in 2003 within the Japan International Cooperation Agency Technical Cooperation (JICA) Project in Romania entitled "Seismic risk reduction for buildings and structures", by the implementing agency National Center for Seismic Risk Reduction (NCSRR, Bucharest) and OYO Seismic Instrumentation Corp., Japan (Aldea et al., 2006a). The equipment consists of a nine channel Kinematrics K2 aquisition station with three triaxial acceleration sensors (Kinematrics FBA-23DH): one installed at ground surface and two in boreholes at -28 m (B1-shallow) and at -78 meters depth (B2-deep). Sampling rate is set at 100Hz, pre-trigger time is 30s, post-event time is 60s, full scale is ±2g and time is set by GPS.

Between 2003 and 2010 at UTC1 station were recorded ground motions from 15 earthquakes with Mw=4.1÷6.0 (14 from Vrancea subcrustal source with focal depths between 60km and 166km, and 1 from Shabla source in the Black Sea, with 10 km focal depth). The main characteristics (reported by National Institute for Earth Physics, Romania) of these seismic events are given in Table 1.1.

Table 1.1. Main characteristics of the seismic events recorded at UTC1 seismic station (2003-2010)

No.	Date	Origin	Origin time (UTC)	Epicenter coordinates		Focal depth (km)	Moment magnitude *Mw*
				Lat. (^{o}N)	Long. (^{o}E)		
1	05/10/2003	Vrancea subcrustal	21:38:18	45.57	26.46	146	4.6
2	10/07/2004		00:34:58	45.69	26.57	150	4.3
3	27/09/2004		09:16:22	45.70	26.45	166	4.6
4	27/10/2004		20:34:36	45.78	26.73	99	6.0
5	14/05/2005		01:53:21	45.68	26.54	148	5.1
6	18/06/2005		15:16:41	45.72	26.66	154	4.9
7	13/12/2005		12:14:45	45.78	26.79	145	4.8
8	18/12/2005		15:09:48	45.40	26.01	78	4.1
9	06/03/2006		10:40:45	45.69	26.64	152	4.6
10	17/01/2007		13:17:21	45.60	26.39	129	4.4
11	14/02/2007		06:56:37	45.49	26.26	150	4.5
12	25/04/2009		17:18:48	45.68	26.61	110	5.0
13	27/05/2009		03:12:50	45:69	26:49	152	4.4
14	05/08/2009	Black Sea	07:49:01	43:41	28:76	1	5.5
15	08/06/2010	Vrancea subcrustal	15:16:09	45:61	26:43	120	4.3

1.2. Ground conditions at the site

The soil profile/stratigraphy at the site is known (Table 1.2), and NCSRR together with 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). The 30m weighted average shear wave velocity is 309m/s. If one considers the whole investigated depth (up to the deep borehole seismic sensor), i.e. 78m, the weighted average shear wave velocity becomes 349m/s. The ground conditions are classified as ground class C "Deep deposits of dense or medium dense sand, gravel or stiff clay with thickness from several tens to many hundreds of m" according to Eurocode 8 and class D "hard soil" according to UBC 1997, these ground classes having an average Vs=180-360m/s. In these codes, these ground classes are associated with a control period of response spectra Tc=0.6-0.8s, that is considered to be unconservative for Bucharest case 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), over 1s in many cases and reaching a maximum of 1.5s. Also, at INCERC station in Eastern Bucharest, Tc values were 1.2-1.38 s for the records of 1977 Vrancea earthquake (Mw=7.4÷7.5). In the Romanian seismic design code P100-1/2006, the Tc value for Bucharest region is 1.6s.

Table 1.2. Soil profile at UTC1 seismic station

Layer thickness (m)	Soil type	Density (g/cm^3)	Vs (m/s)	Vp (m/s)
4.5	silty clay	2.07	270	480
3.5	lime	2.07	270	880
2.7	clayey gravel	2.07	270	880
5.3	sand	2.07	380	1700
1.9	sand	2.07	310	1700
6.1	gravel	2.07	310	1700
9	clay	2.07	340	1700
15	silty sand	2.07	340	1700
14.3	sand	1.95	430	1680
4.7	silty clay	2.08	390	1830
4.5	sand	2.08	390	1830
4.1	silty clay	2.08	390	1830
2.4	clay	2.08	390	1830

2. ANALYSIS OF EARTHQUAKE RECORDS

The acceleration seismic records obtained at UTC1 station during the earthquakes from Table 1.1 were used for the assessment of site response characteristics. In Table 2.1 are given examples of peak ground acceleration values for four records with different amplitude levels, and in Fig.2.1 are exemplified the recorded NS components at ground surface, at -28 m depth and at -78m depth, during the strongest recorded earthquake (27/10/2004, Mw=6).

Table 2.1. Examples of peak ground acceleration (PGA) values at different depths (UTC1 seismic station)

Date	Mw	Δ (km)	Depth/ component	PGA (cm/s2)		
				EV	NS	V
27/10/2004	6.0	160	0m	58.4	34.9	34.4
			-28m	14.6	28.5	11.1
			-78m	23.1	16.5	9.8
25/04/2009	5.0	141	0m	13.0	10.6	9.3
			-28m	5.3	6.3	4.3
			-78m	4.9	5.1	3.6
27/09/2004	4.6	137	0m	7.9	8.8	4.3
			-28m	2.4	3.3	2.1
			-78m	3.6	2.6	1.1
18/12/2005	4.1	105	0m	3.2	2.4	1.0
			-28m	1.0	1.2	0.4
			-78m	1.2	0.7	0.3

Using all the records from the 15 earthquakes in Table 1.1, the peak ground acceleration amplification from depth to ground surface has the characteristics given in Table 2.2.

Table 2.2. Characteristics of peak ground acceleration (PGA) amplification with depth (UTC1 seismic station)

ratio	PGA_{0m}/PGA_{-28m}		PGA_{0m}/PGA_{-78m}		PGA_{-28m}/PGA_{-78m}	
component	H	V	H	V	H	V
mean	2.8	3.2	2.9	3.4	1.1	1.2
coefficient of variation	0.4	0.4	0.6	0.2	0.3	0.3

In all cases from -28m and/or from -78m to the ground surface there was always PGA amplification. However a peculiarity should be signalised, in 10 cases there was a slight reduction of PGA instead of amplification for the EW horizontal components. Overall, there was no correlation between earthquake magnitude and PGA amplification.

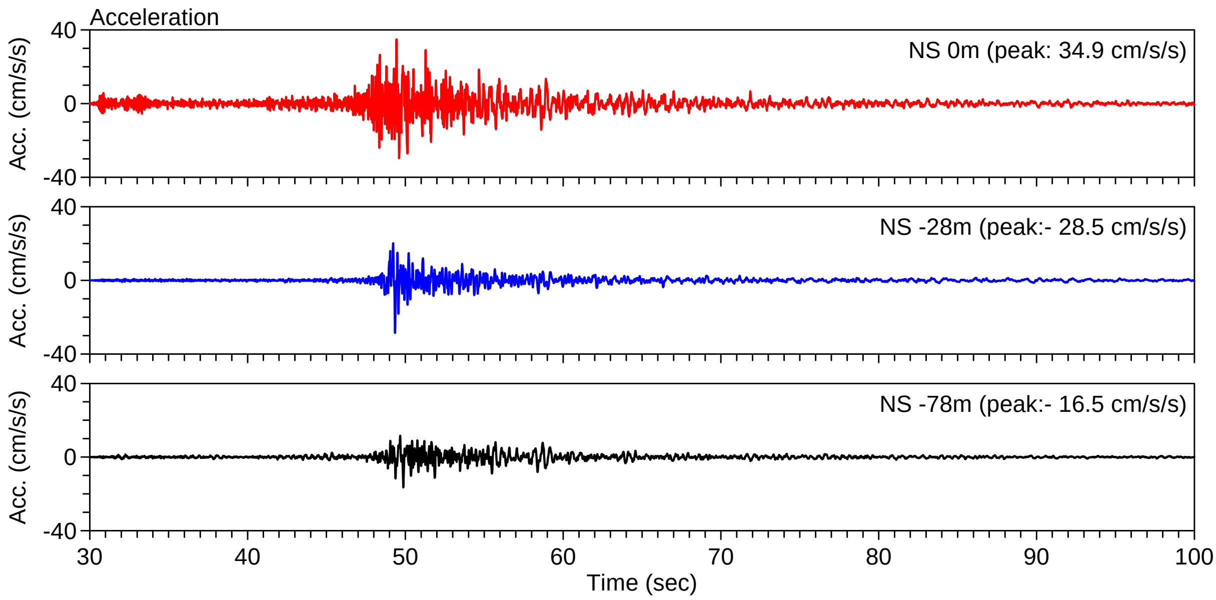

Figure 2.1. UTC1 seismic station. Evolution with depth of accelerograms recorded during 27/10/2004 Vrancea earthquake (Mw=6)

The presented case clearly shows the major contribution of the upper geology (here 28m of soil) to the values of the peak ground acceleration at ground surface.

In what concerns the vertical peak ground acceleration at ground surface, using all the records from the 15 earthquakes in Table 1.1, a 0.74 average ratio PGA_V/PGA_H was obtained (standard deviation 0.21, coefficient of variation 29%). In total, for 17 from 30 ratios (2 horizontal components from 14 earthquakes) the value was larger than 0.7 (value recommended to be considered by Eurocode 8 and Romanian seismic design code P100-1/2006). The maximum value was 1.12, Figure 2.2. Of course no general conclusion can be made, the data coming from only 15 earthquakes recorded at one station.

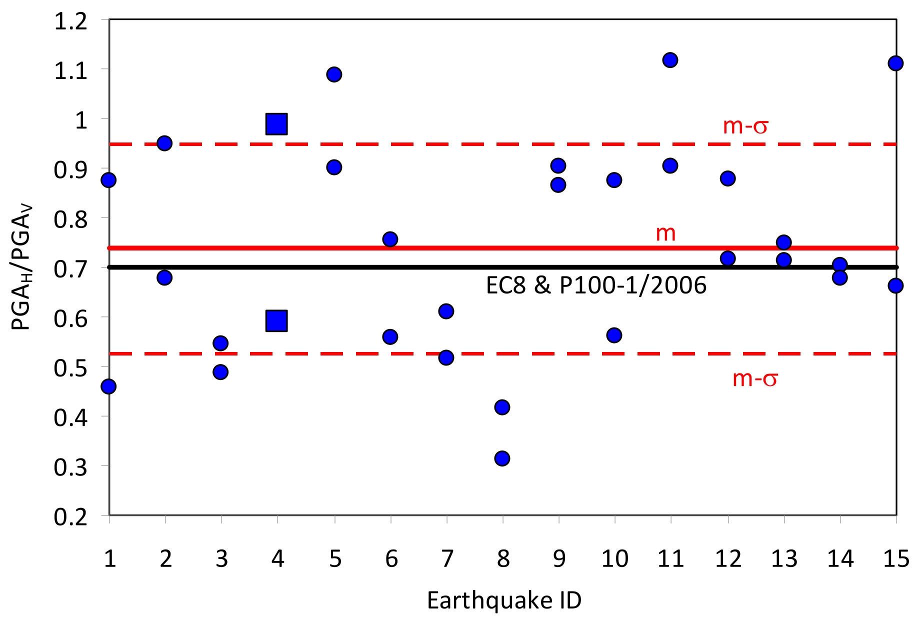

Figure 2.2. UTC1 seismic station. PGA_V/PGA_H ratios
(squares – ratios for the strongest event, Mw=6 Vrancea earthquake - 27/10/2004)

Using all the records from the 15 earthquakes in Table 1.1, the maximum normalized spectral acceleration values were computed: average value is 3.48 (with 18% coefficient of variation).

The 3.48 average value of the maximum normalized spectral acceleration is larger than the 2.875 recommended by Eurocode 8 (i.e., 2.5 S, where soil factor S is 1.15 for ground class C), and the 2.75 recommended by P100-1/2006 Romanian seismic design code (comparisons in Figure 2.3). Again, of course, no general conclusion can be made, the data coming from only 15 earthquakes recorded at one station.

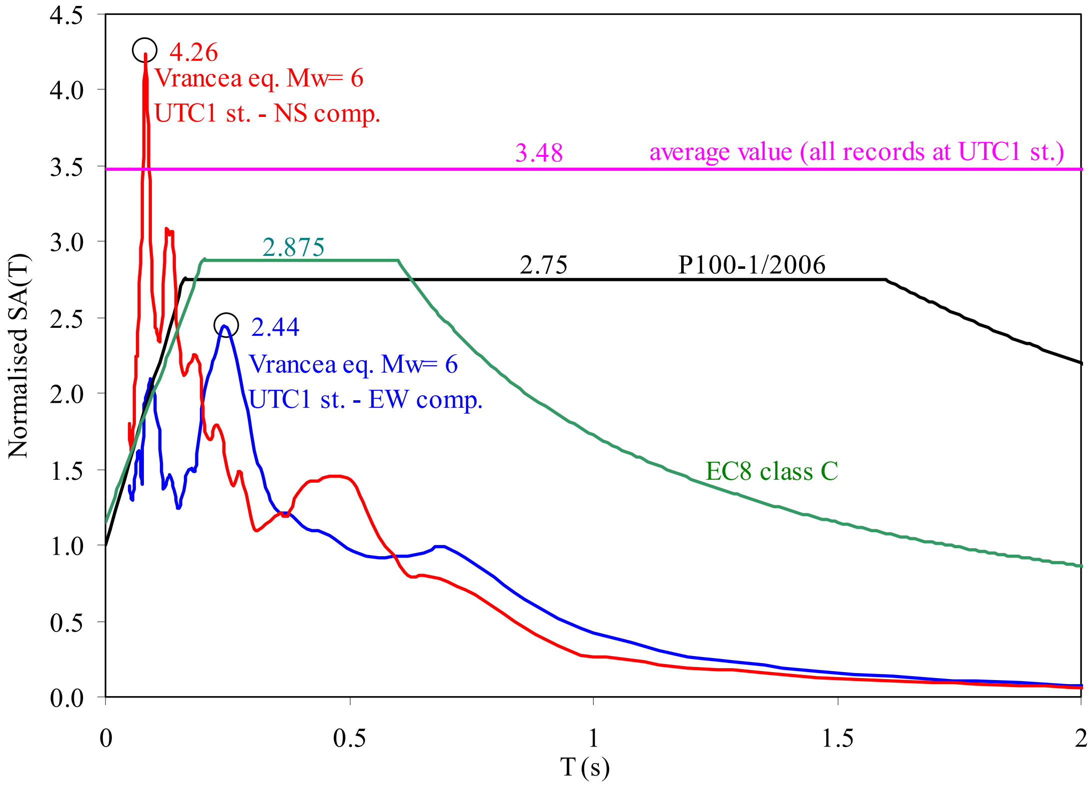

Figure 2.3. UTC1 seismic station. Comparison of normalized response spectra and maximum values

2.1. Surface-borehole spectral ratios

The site response assessment method that uses borehole records (Surface-Borehole Spectral Ratio SBSR) is considered by some authors as the most reliable (Atakan, 1998), while other authors do not recommend it since "the down-hole sensors records include not only the incident waves coming from the source, but also waves reflected from the surface" (Safak, 1997).

The SBSR method is used here for comparison with the single station spectral ratio. One important limitation of the comparison is coming from the fact that the borehole sensor is not located on the bedrock, and consequently the SBSR characterize only the response of the soil profile from ground surface to the borehole sensor.

When using data from 2 different depths, the SBSR method can also show the contribution of soil thickness in the site response.

In Figure 2.4 are presented the SBSR at UTC1 station. All the earthquake records are used, except those of the moderate Mw=6.0 event of 2004. The average ratio is computed for both the shallow and the deep sensor and is compared with the average SBSR of the moderate 2004 event. The comparison indicates that there were no significant non-linear effects in the ground motion recorded during the 2004 event. The figure clearly shows that using only the upper 28m of soil for evaluating the site response characteristics is not sufficient; there is an important shift of the peak frequencies when using the ratio to 78m depth.

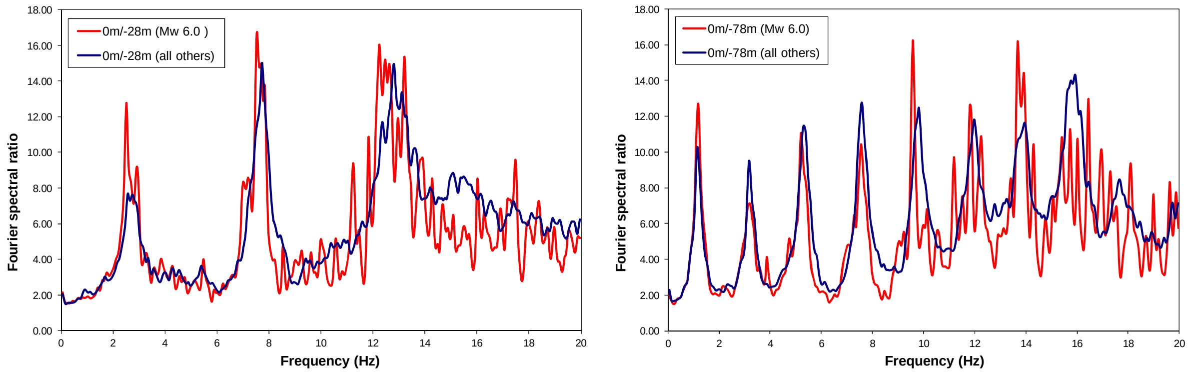

Figure 2.4. UTC1 seismic station. Surface-over-borehole spectral ratios

The frequencies of the identified peaks from the average of al SBRS ratios are given in Table 2.3.

Table 2.3. Peak frequencies from SBSR (UTC1 seismic station)

SBSR	Peak frequencies (Hz)				
0m/ -28m		2.75		7.55	
0m/ -78m	1.16		5.32	7.59	9.81

In Figure 2.5 are presented the averaged SBSR (using all records) in two versions: (i) ground surface over deep borehole and (ii) shallow borehole over deep borehole. It can be observed that the upper 28m of soil practically do not influence the position of peak frequencies. The site response in the low frequency domain is governed by the deeper geology. The spectral ratios between the shallow borehole (-28m) and the deep borehole (-78m) captured nicely the frequency characteristics of ground response, but the amplitudes are in general reduced especially at high frequencies. The higher SBSR amplitudes in the high frequency domain indicate the influence of the upper geology in this frequency range, and consequently the influence on the peak ground acceleration values (previously discussed).

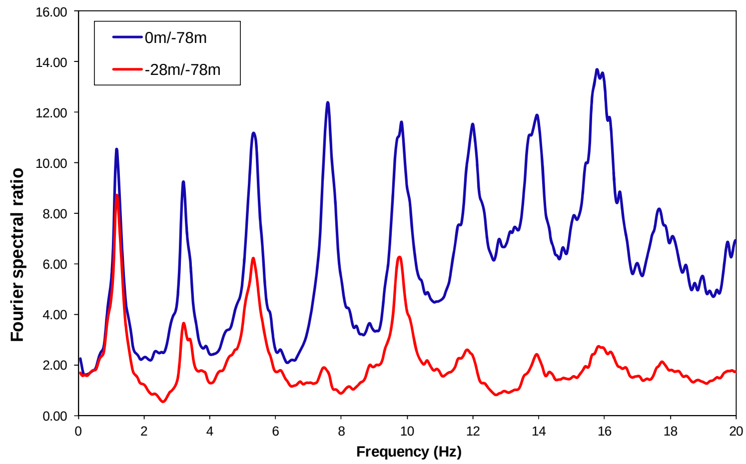

Figure 2.5. UTC1 seismic station. Average surface-over-borehole spectral ratios

In such cases (of sites with deep sediments), it is important to take into consideration the whole depth up to the bedrock for evaluating the site response characteristics. Unfortunately, in most cases such data as the soil profile up to the bedrock and/or ground motion records at ground surface and at bedrock level are not available.

2.2. Single station spectral ratios

In case of Bucharest, no reference outcropping bedrock is available nearby, so the single station spectral ratio may be applied. The single station spectral ratio (H/V of Fourier amplitude spectra), despite a lack in theoretical justification, was tested successfully by an increasing number of authors for soft soil sites (for example Lermo et al., 1993). The basic assumption is that the vertical component of ground motion is not affected by site effects. The evolution with depth of the Fourier amplitude spectra of the vertical components from the record of 27/10/2004 earthquake (Mw=6) is shown in Figure 2.6 (left). Differences between spectra tend to be important appear at frequencies higher than ~1.5 Hz. Bellow 1.5 Hz the Fourier spectra are almost identical, so it may be considered that below these frequencies the H/V spectra could provide valid/useful results. In Figure 2.6 (right) is shown the evolution with depth of H/V spectral ratio at UTC1 site, using the 27/10/2004 earthquake records (EW component). It can be noticed that the upper 28m of soil have limited influence in the low frequency. Some peaks below 1 Hz appear on all the H/V Fourier spectral ratio, due to the deep geology.

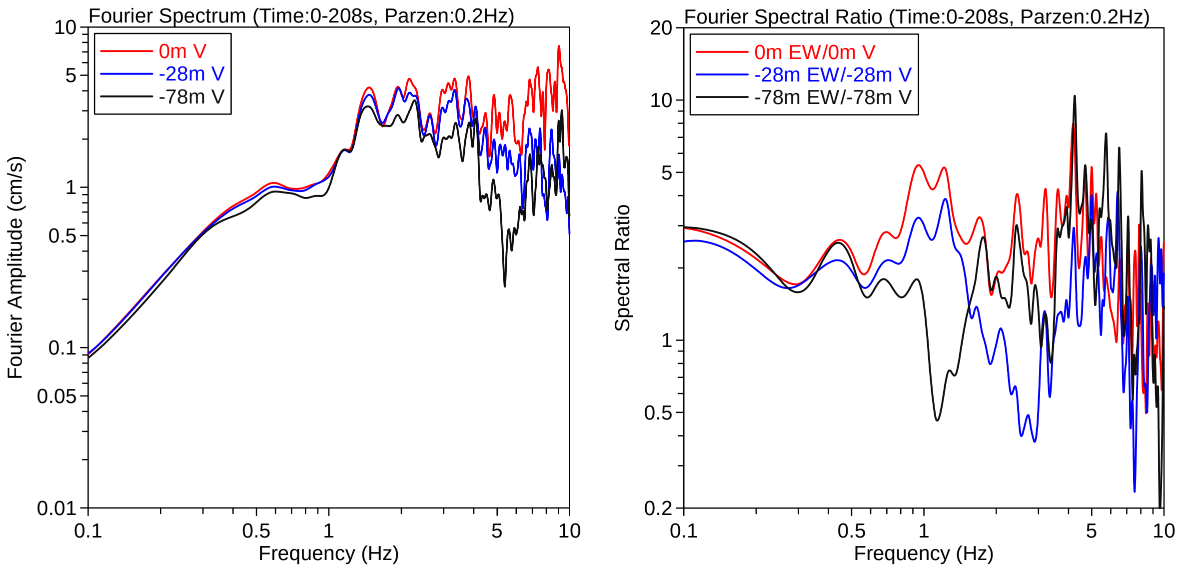

Figure 2.6. UTC1 seismic station. Evolution with depth of Fourier amplitude spectra (left) and H/V spectral ratios (right) – 27/10/2004 Vrancea earthquake (Mw=6)

In Figure 2.7 are shown the H/V spectral ratios for all the records available at UTC1 station, and the average spectral ratio for each component (EW and NS).

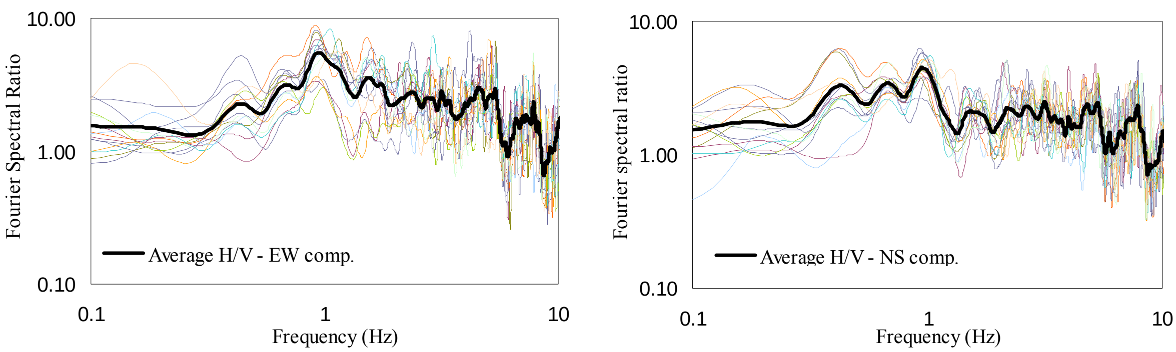

Figure 2.7. UTC1 seismic station. H/V spectral ratios

In Figure 2.8 are compared the average H/V spectral ratios for all the records available at UTC1 station, for each component (EW and NS). The peaks below 1 Hz clearly appear on both ratios, and they can be related to the deep geology, thus such peaks could not be identified with SBSR technique. The following first frequency peaks are identified: for NS component 0.43Hz, 0.68 Hz, 0.95 Hz and 1.51 Hz and for EW component 0.44 Hz 0.7Hz, 0.94 Hz and 1.55 Hz. This confirms the low-frequency (long period) vibration of soil in Bucharest, phenomenon due not only to the source effects but also to the existence of deep sediments.

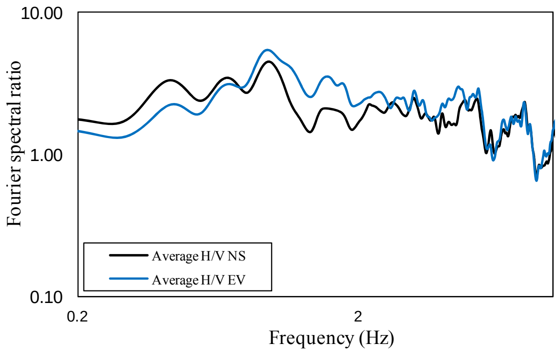

Figure 2.8. UTC1 seismic station. Average H/V spectral ratios

3. ANALYSIS OF AMBIENT VIBRATIONS

Two records of ambient vibration are used here (acceleration records obtained with the seismic station, in 2003 and 2009). The peak accelerations at ground surface are around 0.3 cm/s^2 and, as expected, in the borehole the peak accelerations are almost identical, with values around 0.04cm/s^2. Human noise strongly affects the vibration at ground level. The amplification of the PGA at ground surface with respect to the PGA in boreholes has an average value of 7.3. In Figure 3.1 (left) are shown the average H/V spectral ratios (Nakamura ratio technique, Nakamura, 1989). There are no clear peaks, but one can identify some kind of peak frequencies as follows: 2.1s, 1.32s, 0.96s, 0.79s. The SBSR technique does not bring useful results for these ambient vibration records.

In 2006 a serie of single-station microtremor measurements were performed by NCSRR and Tokyo Soil Research Co., Ltd., at several sites in Bucharest, including UTC1. Each single station microtremor observation consisted of 30 minutes of measurement, and H/V Nakamura ratio was computed for the undisturbed data segments. FFT was computed with 32,778 points and 50% overlapping of each selected time-window. The H/V microtremor spectral ratios (Figure 3.1 - right) indicate peaks in the long period range (~1-2s & ~5-6s).

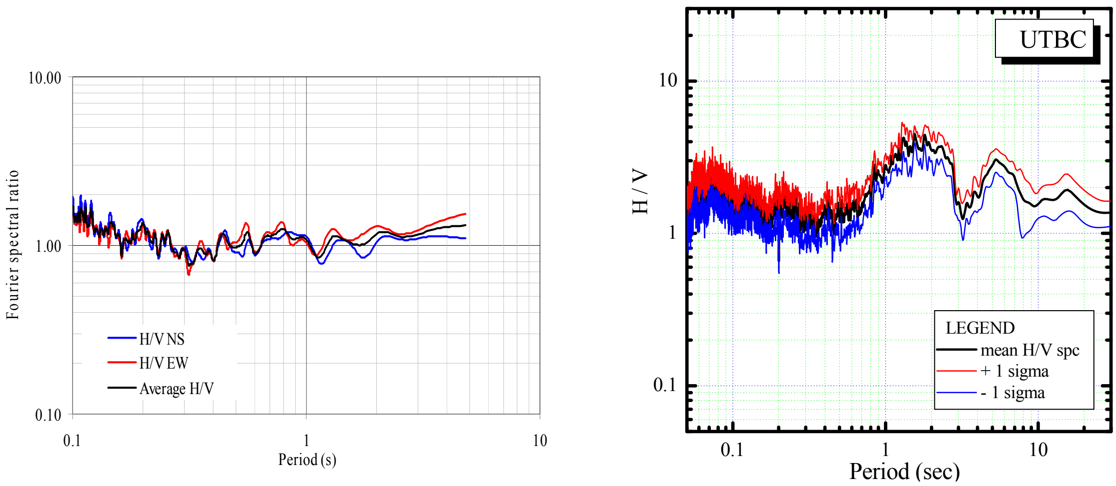

Figure 3.1. UTC1 seismic station. Average H/V spectral ratios for ambient vibrations (accelerations – left, velocities – right)

4. ANALITYCAL SITE RESPONSE ASSESSMENT

Using the soil profile (Table 1.2) and soil behaviour curves from literature (EPRI 1993, Vutecic&Dobry 1991, Seed et al., 1986), equivalent linear site response computations were performed using EERA application (Bardet et al., 2000). Bellow 78m depth an elastic bedrock was considered, with Vs=400m/s and 21kN/m^3 total unit weight (variation of these properties do not affect the results).

Two analyses are exemplified here, one for the strongest recorded event (27/10/2004, Mw=6.0, NS comp.) and one for the smallest (18/12/2005, Mw=4.1, NS comp.). The input motion was considered at -78m, and the surface motion was obtained through convolution. The maximum shear strain was 0.0055% and damping remained below 3% in case of the stronger ground motion and 0.00051% and, respectively below 1.2% in case of the less strong ground motion. Thus one can say that soil behaviour was practically elastic.

In Figure 4.1 are displayed the evolutions with depth of the maximum accelerations for the two considered cases: 27/10/2004 (left) and 18/12/2005 (right). One may notice that there are differences between the computed and the recorded peak ground accelerations, and since the soil behaviour is cvasi-elastic, one explanation may be the existence of some degree of imprecision in the definition of the soil profile.

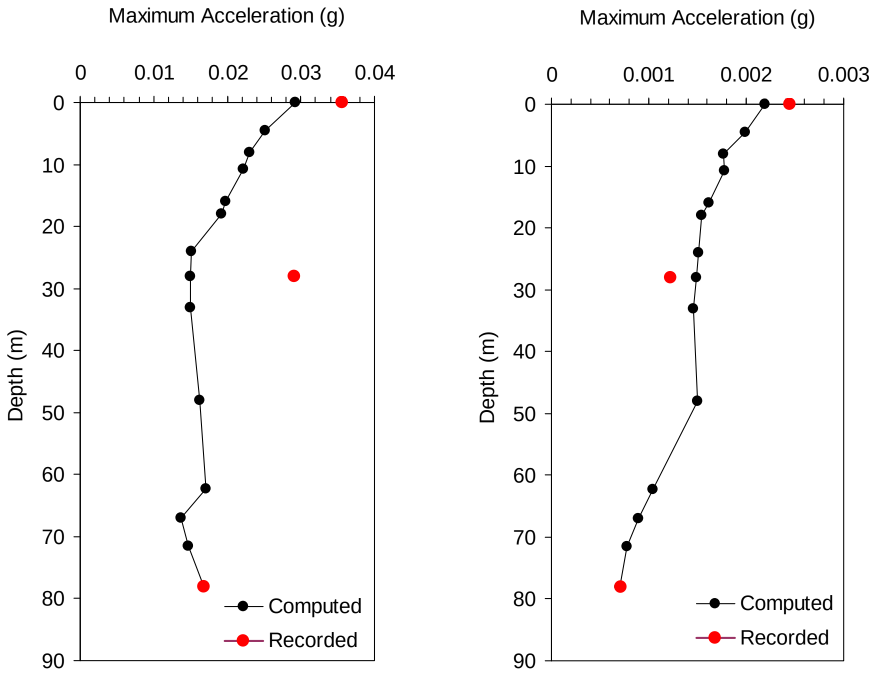

Figure 4.1. UTC1 seismic station. Evolution with depth of the maximum accelerations – 27/10/2004 earthquake (left) and 18/12/2005 earthquake (right) – NS components

In Figure 4.2 are comparatively presented the transfer functions (ground surface-to -78m Fourier amplitude spectral ratios) for the two cases. One may notice the reasonable agreement in what concerns the peak frequencies, especially for the first one.

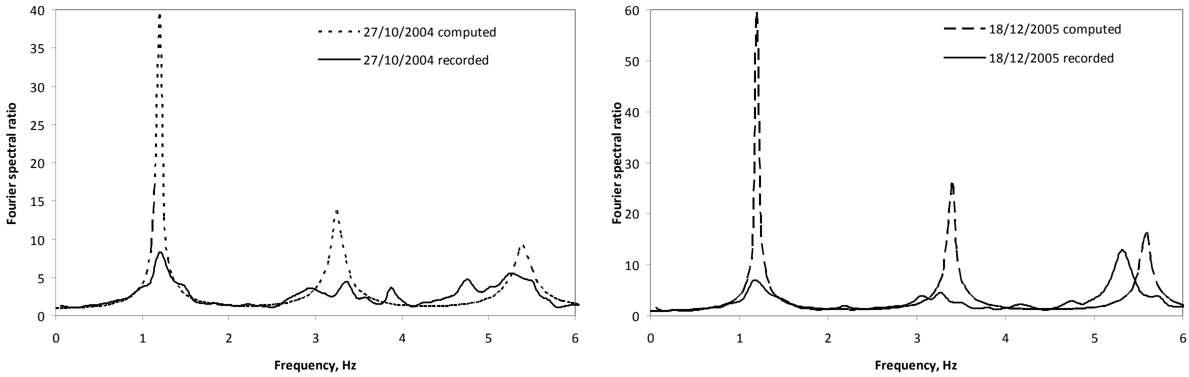

Figure 4.2. UTC1 seismic station. Computed and recorded surface-over borehole spectral ratios

5. FINAL REMARKS

The site response at the studied site in northern Bucharest is characterised by low-frequencies (below 1Hz) of ground vibration identified from earthquake single station spectral ratios and from ambient vibrations. The surface-over borehole spectral ratios could not capture these low peak frequencies due to the fact that the borehole sensor is at only 78m depth, while sediments at the site are much deeper. The upper geology (28m in this case) significantly affects the peak ground acceleration at ground surface, but is not sufficient for characterising the site response.

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