

Earthquake Induced Site Effect in the Algiers–Boumerdes Region: Relation Between Spectral Ratios Higher Peaks and Observed Damage During the May 21st M_w 6.8 Boumerdes Earthquake (Algeria)

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Abstract—The Algiers–Boumerdes regions were hit by an M_w 6.8 destructive earthquake on May 21, 2003. The accelerometric and seismometric networks successfully recorded the main shock and many aftershocks at some locations where the damage was most extensive. A microtremor measurement was performed in the same locations; some of them are localized on the Mitidja basin. In this paper, we propose to analyze earthquake-induced site effect derived from horizontal to vertical spectral ratio from ambient noise (noise horizontal to vertical—NHV), or from very weak, weak, moderate and strong (peak ground acceleration—PGA >10 % g) seismic motions (EHV), and transfer function evaluation from soil velocity profile data at four sites. H/V spectral ratios are computed by using both Fourier and response spectra. Compared to the transfer function, the obtained results show that in the case of soft soils, NHV as well as EHV give a good estimation of the soil's fundamental frequency, whereas the NHV underestimate the H/V amplitude and the EHV amplitude increase with the seismic motion intensity. In the case of firm soils, whereas the NHV gives flat curves synonymous for a rock site or a bump, the EHV is more appropriate as seen by identifying clear peaks with non negligible amplitude. In the case of soft sites as well as in the case of firm sites, strong peaks at frequencies higher than the fundamental one are found from EHV curves. Those peaks would not be found when looking at NHV ratios alone, are evidenced by the computed transfer function as well as by an analytical formulation, and are in agreement with the observed distribution of damage during the M_w 6.8 2003 Boumerdes earthquake. Finally, the same analysis is performed by using response spectra rather than Fourier spectra and leads to the same conclusions. Moreover, the calculation of the response spectra is more easily compared with the smoothing operation of the Fourier spectra.

Key words: Microtremor, HVSr, seismic motions, RFT, site effect, higher peaks, Boumerdes, Algiers.

1. Introduction

It is known that soft soil deposits can considerably amplify earthquake ground motion and consequently increase the damage suffered during earthquakes, which is often referred to as site effect. The microtremors based technique has been known since the early seventies (NOGOSHI IGARASHI, 1970, 1971; UDWADIA and TRIFUNAC, 1973) and reviews on the method can be found in BARD (1999) or MUCCIARELLI and GALLIPOLI (2001). Firstly, the Horizontal-to-Vertical spectral ratio method (H/V) for site effect estimation was based only on microtremor recordings, and recently it has been extended to the use of earthquake recordings (OHMACHI *et al.*, 1991; FIELD and JAKOB, 1993; THEODULIDIS and BARD, 1995; LACHET *et al.*, 1996; SEEKINS *et al.*, 1996; BONILLA *et al.*, 1997; PILZ *et al.*, 2009). Two techniques are used depending on the kind of data, in the case of microtremors it is called NHV (NAKAMURA, 1989), while in the case of seismic motion records, it is called receiver function technique (EHV). The latter, used mainly for accelerations, has been extended to velocities and displacements (HUANG *et al.*, 2002). It has been shown (BARD, 1999; HAGSHENAS *et al.*, 2008; GOSAR and MARTINEC, 2009) that NHV can supply useful information about the resonance properties of the shallow subsoil and represents a cost-effective tool for microzoning studies and site classification (FUKUSHIMA *et al.*, 2007; D'AMICO *et al.*, 2008), and can retrieve information on the subsoil seismic layering (ARAI and TOKIMATSU, 2004, 2005; PAROLAI *et al.*, 2005; PICOZZI and ALBARELLO, 2007; HERAK, 2008). On the other hand, the NHV has been studied to explain its strengths and limitations

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(BONNEFOY-CLAUDET *et al.*, 2006; CADET, 2007; BARD, 2008; PILZ *et al.*, 2009; LUNEDI and ALBARELLO, 2010). Furthermore, an important aspect that has attracted much attention in recent years is the physical interpretation and modelling of the NHV curve deduced from ambient vibrations. Some arguments support the idea that the NHV curve is controlled by body waves (NAKAMURA, 2000; HERAK, 2008), while other arguments suggest that it is controlled by surface waves (ARAI and TOKIMATSU, 2004, 2005; LUNEDI and ALBARELLO, 2010). These analyses indicate that the surface wave's approximation seems to produce reliable results for frequencies larger than the fundamental resonance frequency of the sedimentary layer and the body waves provide better results around the resonance frequency.

In general, when we deal with NHV curves, we are interested about the analysis of the largest peak because it gives useful information about the fundamental frequency. In the case of the Boumerdes site, two studies dealing only with microtremor measurements have been published and concerned with the epicentral area of the 2003 Boumerdes earthquake (GUILLIER *et al.*, 2005; HELLAL *et al.*, 2010). The NHV results show only one (01) peak identifying a resonance frequency which is not comparable with the building fundamental frequency. Their conclusion was that the observed great damages are not related to the site effect. However, the EHV shows other secondary peaks, comparable with the building fundamental frequency, with stronger amplitude which could be related to the soil's higher modes.

PILZ *et al.* (2009) have already identified clear higher peaks from earthquake data and supposed that they correspond to the eigenfrequency of the surrounding buildings. In this paper, we deal with site effect based on the recorded seismic motion spectral ratio and we focus on the identification of higher peaks, their relation with the soil higher modes and their correlation with the observed damages during the May 21st 2003 Boumerdes earthquake ($M_w = 6.8$). Additionally, we analyse the directionality effect on the earthquake horizontal to vertical spectral ratio (EHV).

Algeria is located on the northern edge of the African plate, which is converging with the European plate since the Mesozoic, with a shortening rate of

about 4–8 mm/year (ANDERSON and JACKSON, 1988; PHILIP, 1987; ARGUS *et al.*, 1989). Northern Algeria is a highly seismic area, as evidenced by recent seismic hazard studies and the historical (1365–1992) seismicity (BOUHADAD and LAOUAMI, 2002; CRAAG, 1994; BENOUAR, 1994). During the last three decades, it experienced several destructive moderate-to-strong earthquakes. On May 21, 2003, the Algiers–Boumerdes region was struck by a magnitude 6.8 (M_w) earthquake, which caused considerable damage and claimed over 2,300 lives. The earthquake was located offshore, next to the coastline, with a reverse fault focal mechanism striking NE–SW and dipping SE (USGS). The main shock was followed by numerous aftershocks, some of them with magnitude over 5.0. It triggered liquefaction in the epicentral zone and a tsunami of up to 1.5 m height along the coast of Spain.

Site effects were observed at some instrumented sites localized on the Mitidja basin where the recorded acceleration was high compared with other instrumented sites at the same hypocentral distance. The Mitidja basin is part of the Tell Atlas, an east-northeast-trending, fold-and-thrust belt along the plate boundary in North Africa. The Quaternary tectonics, reverse faulting, and related north-northwest-south-southeast compression movements are consistent with thrust focal mechanisms of recent earthquakes that result from the 4–8 mm/year of convergence of Africa toward Eurasia. The Mitidja basin is bounded to the south by the Blida fold-and-thrust system, which corresponds to imbricated southeast dipping thrust sheets. The northern side of the flat basin is limited by the Sahel active fold parallel to the coast (AYADI *et al.*, 2003).

In this study, we propose to analyze the earthquake-induced site effect derived from the H/V spectral ratio from ambient noise (NHV), and from very weak to strong ($PGA > 10\%$ g) earthquake ground motions (EHV). They are compared with transfer function evaluated from the soil velocity profile data at four sites where the damage was most extensive. H/V spectral ratios are computed by using Fourier spectra and response spectra. Also, we will check the influence of the directionality effect of the seismic motion on the H/V spectral ratio, and finally we investigate the correlation of the higher modes with the observed damages.

2. Methodology

In order to evaluate the EHV and the NHV spectral ratios we follow these steps: (1) choice of strong phase of the signal in the case of seismic recordings by using a window length greater or equal to 5 s, while for the microtremor recordings stable windows are picked out, with a 20 s long window; (2) for each window, we calculate the Fourier amplitude; (3) the obtained spectra are then smoothed with the Konno–Ohmachi model (KONNO and OHMACHI 1998) in order to eliminate the imaginary peaks which can bias the spectral analysis; (4) we calculate the spectral ratios for each window (East–West/Vertical and South–North/Vertical); (5) we calculate the average between the two spectral ratio components (Eq. 1); (6) finally, we calculate the geometrical mean of the obtained spectral ratios.

$$SR_A = \sqrt{SR_{E-W}^2 - SR_{N-S}^2} \quad (1)$$

where, SR_{E-W} , SR_{N-S} are the east–west and north–south H/V spectral ratios components, respectively.

We also calculate the H/V ratio of the pseudo response spectrum (damping of 0.05) using the accelerometric data recorded in the sites of interest during the 21 May Boumerdes mainshock and aftershocks. Their mean and standard deviations are computed as for spectral ratios of Fourier amplitude (step iv to vi, previous paragraph).

3. Stations and Data Acquisition

The Boumerdes earthquake was felt as far as 250 km from the epicenter, where accelerations of about 0.02 g have been recorded. Among the CGS (LAOUAMI *et al.*, 2006) stations that recorded the earthquake, four were selected for this study (Table 1),

Table 1

Geographical coordinates of the studied sites

Site coordinates	Hussein Dey (firm soil)	El Affroun (soft soil)	Dar El Beida (soft soil)	Boumerdes (firm soil)
Latitude	36.74°	36.469°	36.716°	36.756°
Longitude	3.096°	2.632°	3.206°	3.473°

located in the areas of Boumerdes, Algiers and Blida from 20 km up to 80 km away from the epicenter (Fig. 1). According to the geological background shown in Fig. 1, the area where these stations are located is comprised mainly of Quaternary and Neogene formations. Quaternary formations, which are generally soft deposits, consist of mostly sand, gravel, and sandy clay covering Plaisancian (lower Pliocene) blue marl and Cristalloyphyllian rocks; they extend to 30 m beneath the ground surface and concern essentially the Dar el Beida and El Afroun stations. Neogene formations concern Husein Dey and Boumerdes stations (MESLEM *et al.*, 2010).

Out of the four seismic stations, detailed soil profiles are only available for three (Fig. 2): Hussein-Dey (up to –58 m), Dar El-Beida (up to –60 m), and Boumerdes (up to –25 m). Shear-wave (S-wave) velocity profiles are only available for one station, Hussein-Dey, and were obtained from in situ down-hole measurements. For Dar El-Beida and Boumerdes, generalized S-wave velocity profiles were estimated using the standard S-wave velocity with respect to geological layers; these were proposed for Algiers province by the Japan International Cooperation Agency (JICA) in cooperation with CGS (JICA and CGS, 2006; MESLEM *et al.*, 2010). Because the uncertainty related to the correlation between the geological and geophysical soil profile and the limited soil profile depth (25 m), we used for the Boumerdes site the S-wave velocity profile estimated by GUILLIER *et al.* (2005) who resolved two interfaces at 37 and 118 m depths, respectively, from microtremor array measurements (Table 2).

According to the Algerian design code site classification (Règles parasismiques algériennes RPA99 (2003)) (Table 3), both Boumerdes and Hussein Dey station soils are firm, while the Dar el Beida and El Afroun station soils are soft. Based on the S-wave velocity profiles, the transfer function, defined as the ratio of the surface motion with respect to the rock outcrop motion, was calculated for three stations using the computer program SHAKE91 (IDRISS and SUN, 1992).

We used in this work three kinds of recordings: microtremors recorded by a K2 station and lenartz-1s sensor, for a duration of 15 min, accelerometric records from ETNA accelerographs (200 Hz natural

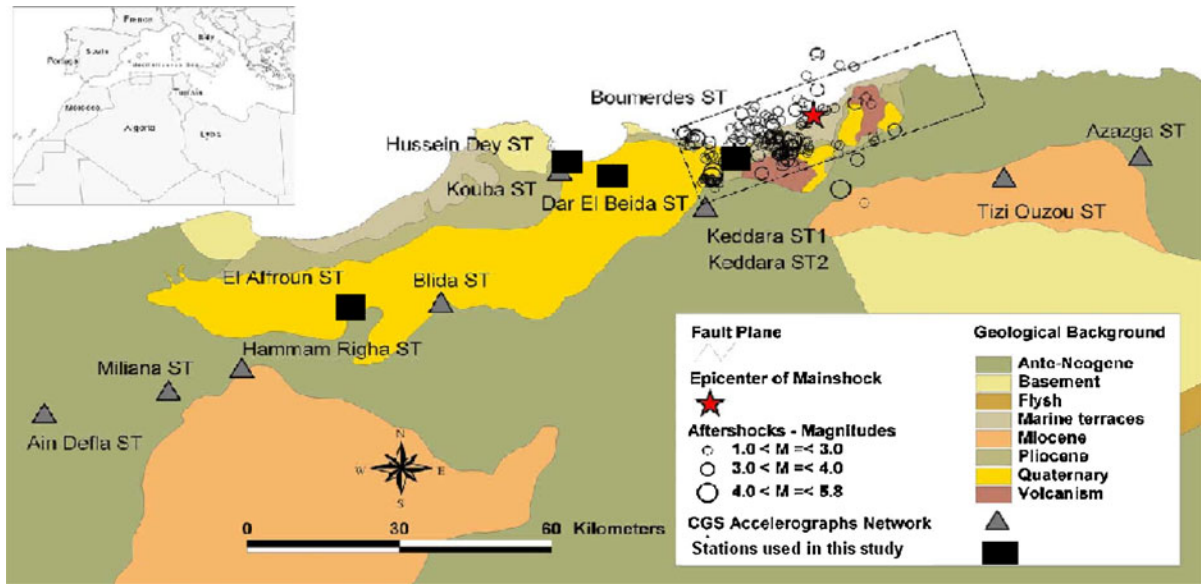


Figure 1

Geological background (AYADI *et al.*, 2003) of the epicentral area and the mainshock's epicenter (starred) of the 2003 Boumerdes, Algeria earthquake. The *rectangle* represents the estimated fault plane (reverse-faulting mechanism; (DELOUIS *et al.*, 2004). The *triangles* represent the CGS accelerograph network stations located in the central part of northern Algeria in 2003. The *squares* represent the four stations used in this study. Note that the stations Dar el Beida, El Afroun and Blida are located on the Mitidja basin (yellow). (Redrawn from MESLEM *et al.*, 2010)

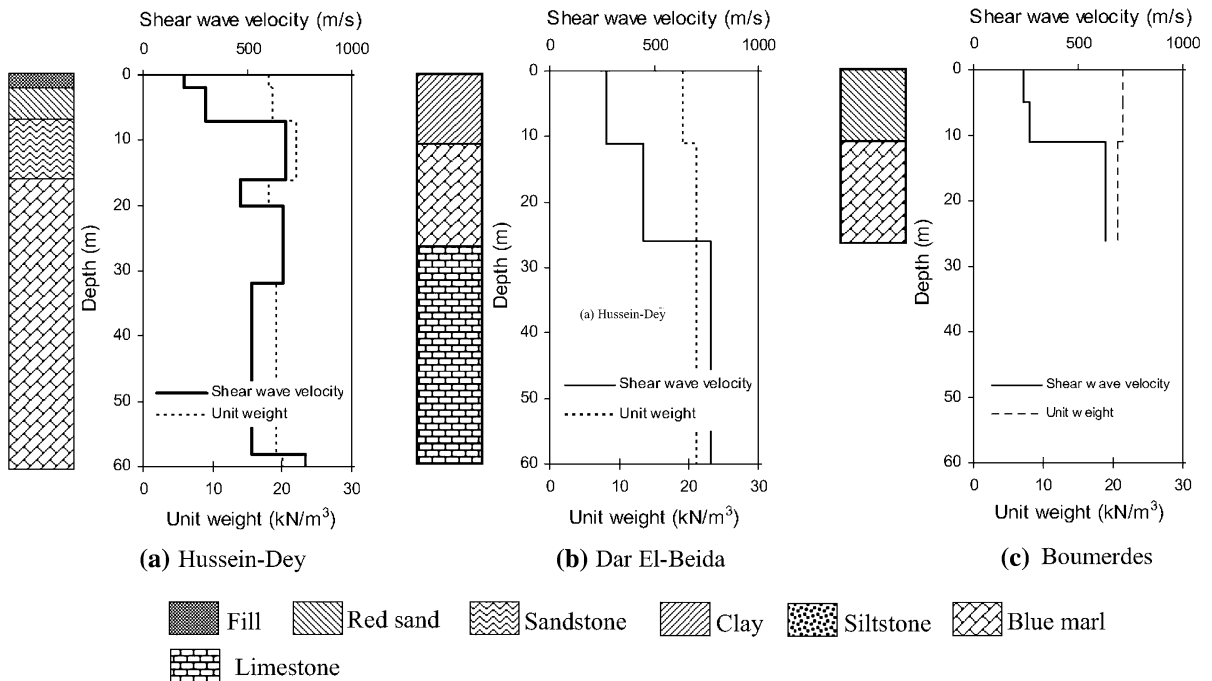


Figure 2

Soil classifications and S-wave velocity profiles for three seismic stations in the Hussein Dey, Dar el Beida and Boumerdes sites. At the Hussein Dey site, the measured S-wave velocity (*thick line*) was measured by a downhole survey. At the Dar el Beida and Boumerdes sites, the estimated S-wave velocity (*thin line*) used existing engineering classification models for different geological units in these areas (JICA and CGS, 2006)

Table 2

Average parameters derived from the 134 m array dispersion curve inversion for Boumerdes site (GUILLIER et al., 2005)

Layer	Depth (m)	V_s (m/s)	Damping ratio ξ	Density (kg/m^3)
Sediment 1	37	300	0.03	1,600
Sediment 2	118	610	0.03	1,900
Halfspace	–	2,100	0.01	2,500

Table 3

Site classification (RPA99 2003)

Type of site	Description	V_s (m/s)
S ₁	Rock site	≥ 800 m/s
S ₂	Firm site	≥ 400 m/s starting from 10 m of depth
S ₃	Soft site	≥ 200 m/s starting from 10 m of depth
S ₄	Very soft site	< 200 m/s in the first 20 m

frequency, 0.7 damping), and seismometric records from a K2 station and lenartz-1s sensor called hereafter “Seismogram”.

The accelerometric and the seismometric data have been recorded by the Algerian accelerograph network monitored by CGS, during the main shock and after-shocks of the 2003 Boumerdes ($M_w = 6.8$) earthquake. In order to analyse the influence of the seismic motion amplitude on the EHV, the accelerometric records are classified following the PGA as very weak, weak, moderate and strong motion (Table 4). The data number availability is shown on

Table 4

Events classified from strong motion to very weak motion with PGA in (% g)

Event	Strong motion	Moderate motion	Weak motion	Very weak motion
PGA (% g)	≥ 10	[5, 10]	[2, 5]	< 2

Table 5

Data number availability in the four sites

Data site	Microtremors (15 min)	Very weak motion	Weak motion	Moderate motion	Strong motion	Seismograms
Hussein Dey	3	12	1		1	20
El Affroun	4	14			1	
Dar El Beida	2	15		3	2	39
Boumerdes	2	104	16	5	5	5

Table 5 and the 3-components PGA, PGV and PGD recorded during the main shock by the four stations are in Table 6.

As an example, Figs. 3, 4, 5, 6 show the E–W, N–S and Vertical time series and the corresponding Fourier amplitude accelerations recorded by the four stations during the M_s 4.5 December 1 2004 aftershock. They are located 6.5, 28, 34 and 71 km from the hypocenter and have, respectively, a PGA of 370, 72, 5.2 and 7.8 cm/s^2 . The time histories plots show a fast decrease of the PGA with distance except for the El Afroun station due to the site effect. Indeed, the recorded PGA at El Afroun is 1.5 times higher than at Hussein Dey, even though the hypocenter distance is twice as large. Also, the Dar el Beida and Hussein Dey stations have close hypocenter distances but very different peak ground acceleration due certainly to a site effect characterising the Dar el Beida station, located in the Mitidja basin. In the frequency domain, we compute the Fourier amplitude (FA) at the different sites for the three components and we consider the peaks evidenced by both the EW and NS directions. The Boumerdes FA shows a higher peak at 5–6 Hz and other peaks at 1.2, 3.9, 5.6 and 7 Hz, the Dar el Beida FA shows peaks at 2.4, 4.2, and 7 Hz, the Hussein Dey FA shows peaks at 3 and 10 Hz, and the El Afroun FA shows peaks at 3 and 8 Hz. The spectral shape similarity between the Dar el Beida and El Afroun stations is probably due to their locations on the Mitidja basin, which is not the case for the other stations.

4. Results and Analysis

We first apply the H/V technique over ground motion data (EHV) and ambient noise (NHV) recorded at the four stations. Later we compare

Table 6

Recorded peak ground accelerations, velocities and displacements during the main shock of the Boumerdes earthquake at the studied sites

Station/hypocentral distance in km/station type	East–West			Vertical			North–South		
	A (g)	V (cm/s)	D (cm)	A (g)	V (cm/s)	D (cm)	A (g)	V (cm/s)	D (cm)
Dar El Beida/29/SMA	0.52	27.5	9.1	0.16	10.7	4.4	0.46	40.6	16.8
Hussein Dey/36/SMA	0.27	16.5	3.9	0.09	7.7	1.8	0.23	9.1	2.7
El Afroun/86/SSA	0.16	5.0	0.4	0.03	1.2	0.1	0.09	5.4	0.3

The main shock was not recorded at the Boumerdes station due to an instrument problem

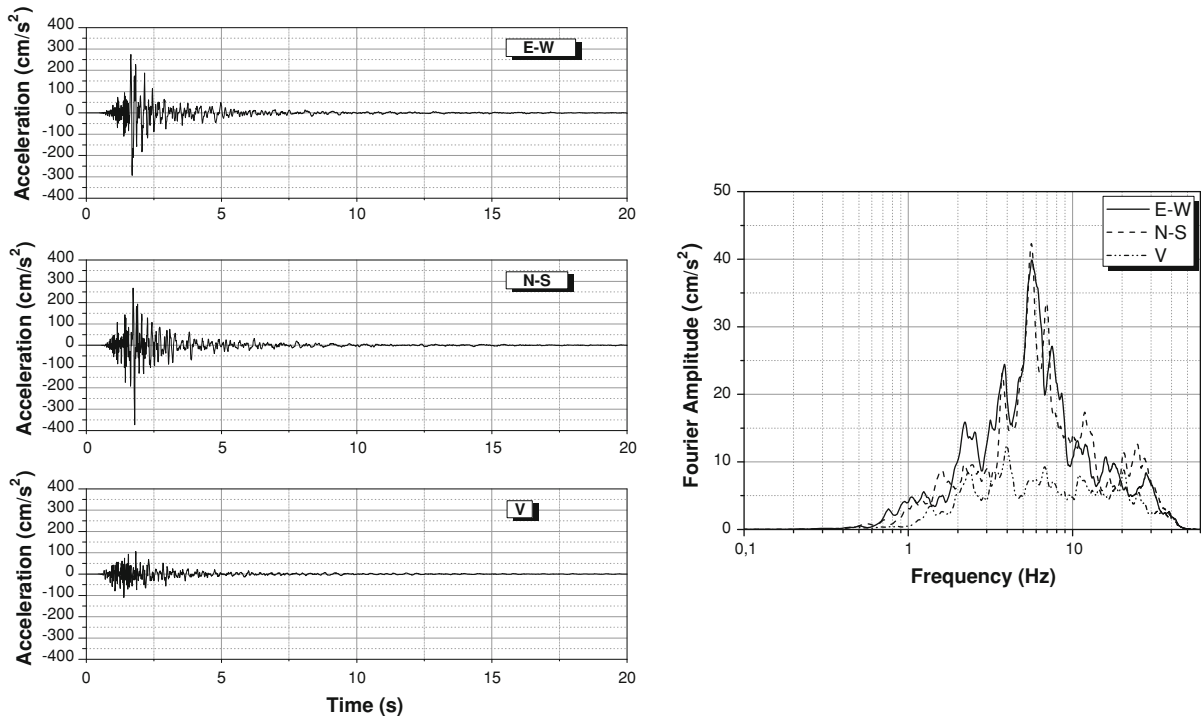


Figure 3

Time series and Fourier amplitude recorded during 12012004 M_s 4.5 earthquake by Boumerdes station located at 6.47 km far from the fault

the NHV and EHV curves to the transfer functions obtained from seismic analysis performed for three sites by using the well known Shake91 software. In doing so, we employ both Fourier and response spectra of the records (FÄH and SUHADOLC, 1994).

Results are shown on Figs. 7, 8 for Boumerdes station, Figs. 9, 10 for Dar el Beida station, Figs. 11, 12 for Hussein Dey station, and Figs. 13, 14 for El Afroun station. In the following we describe the results inferred from the horizontal-to-vertical spectral ratio curves.

4.1. Directionality Effect

In a previous study related to the strong motion data analysis during the May 21 2003 Boumerdes earthquake, LAOUAMI *et al.* (2006) found that the recorded PGA were higher on the E–W component, than on the N–S one (Table 6) and suggested a directional effect related to the fault orientation, and well correlated with the post-seismic observations which reveal a NE–SW trend of the damaged area. In the present study, we investigated the directional variation of both EHV and NHV. We plot the

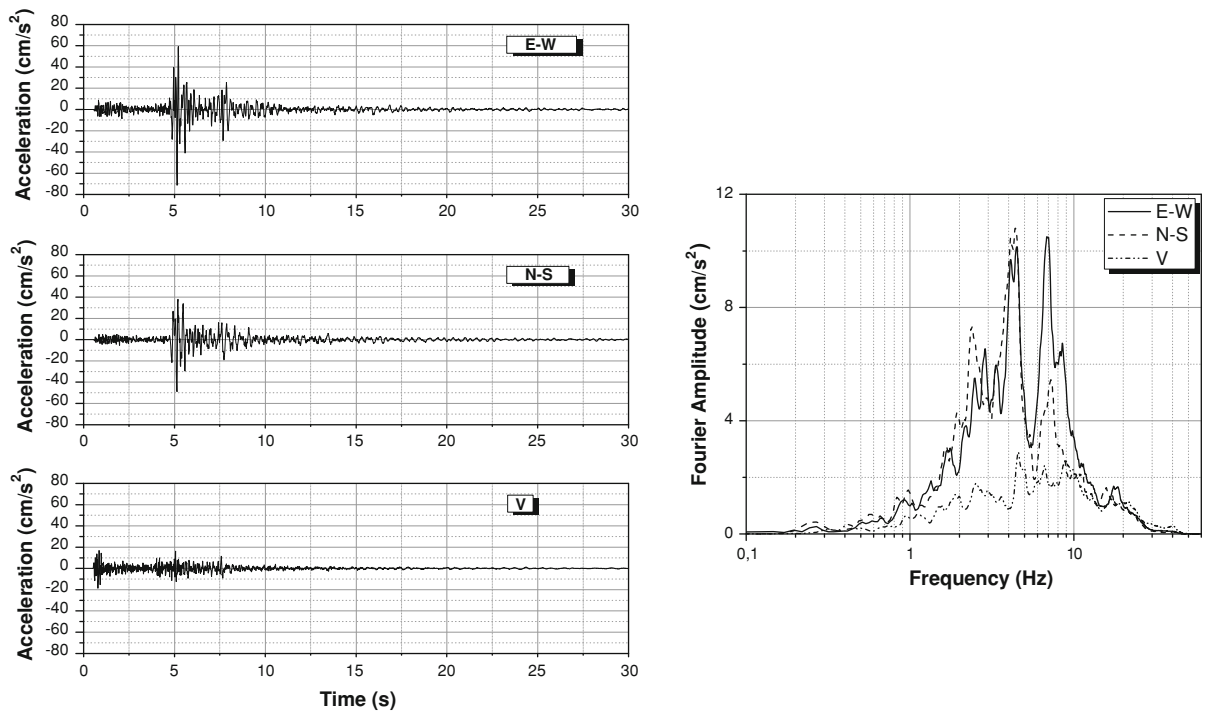


Figure 4

Time series and Fourier amplitude recorded during 12012004 M_s 4.5 earthquake by Dar el Beida station located at 28 km far from the fault

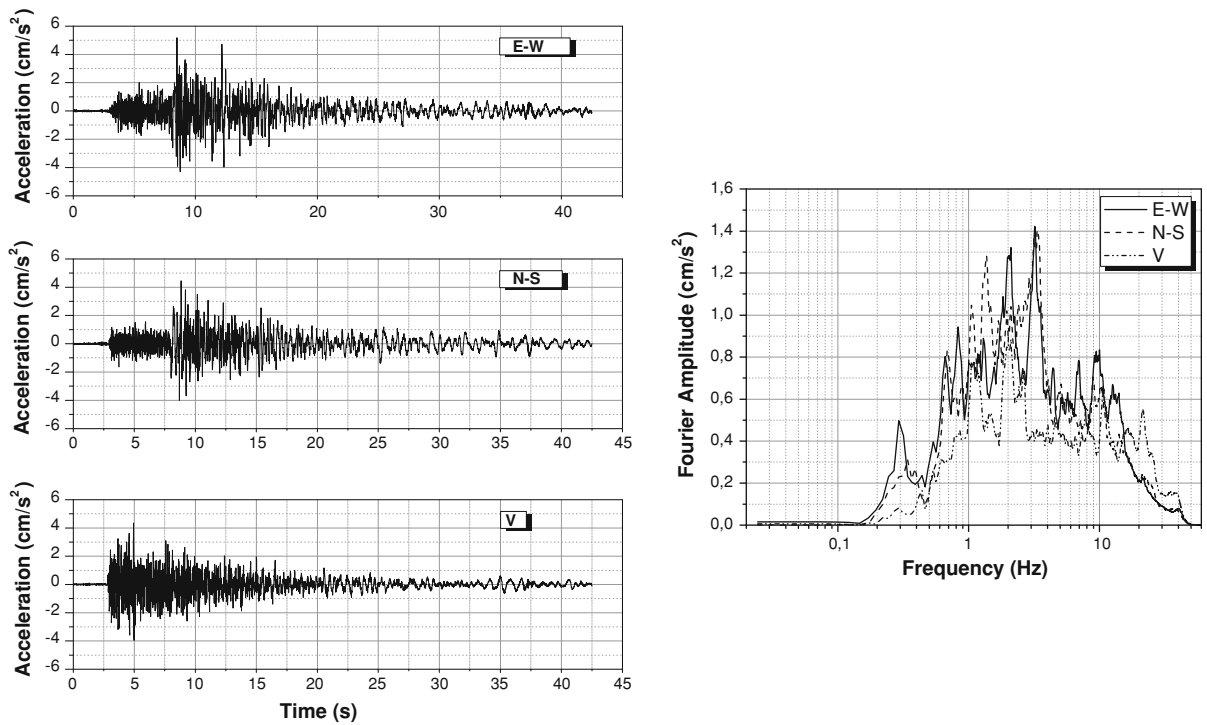


Figure 5

Time series and Fourier amplitude recorded during 12012004 M_s 4.5 earthquake by Hussein Dey station located at 34 km far from the fault

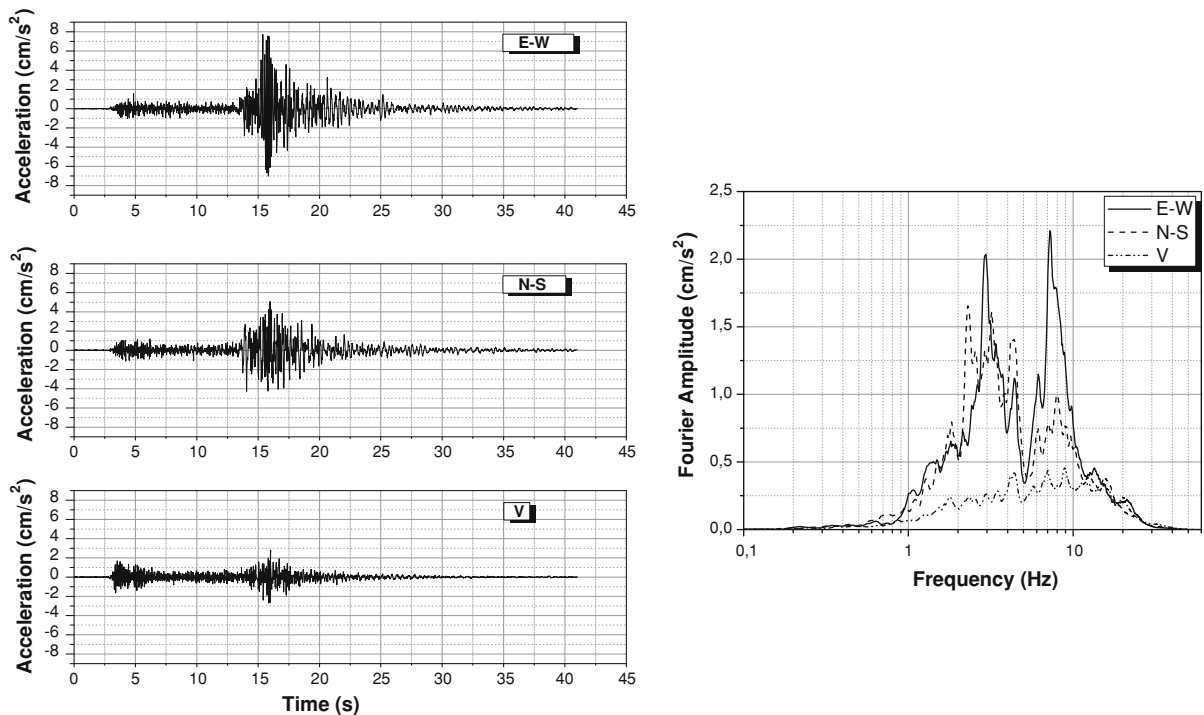


Figure 6

Time series and Fourier amplitude recorded during 12012004 M_s 4.5 earthquake by El Afroun station located at 71 km far from the fault

comparison between the strong motion and the microtremor for the four sites of interest. It appears that the amplitude in the E–W direction (Figs. 7, 9, 11, 13) is in general, more important than in the N–S one in the case of seismic motion (EHV). Otherwise, in the case of the noise, NHV curves in the two directions exhibit both a similar trend and the same amplitude level and corroborates the study of GUILLIER *et al.* (2005). In the case of seismic motion, the considered earthquakes have the same focal mechanism and source-to-site distances, suggesting that the difference can be related to a fault directional effect and not to a local site effect. Also, the experimental observation shows the effect of directionality for different path and different soil types.

4.2. Site Amplification

The H/V approach applied to records of earthquakes, or receiver function technique, is a very useful tool for estimating local site characteristics, especially when no reference station is available. Microtremor measurements are also a reliable tool to

find the resonant frequency of a site via the HVSr approach, but not to give the amplification of the seismic ground motion. In what follows, the NHV and EHV curves are compared to the computed transfer functions, except for the El Afroun station because no soil velocity profile is available for this site. Firstly, we observe for the four stations that the EHV amplitude increases with the seismic motion intensity (Figs. 8, 10, 12, 14). In a recent study (MESLEM *et al.*, 2010), the analysis of the predominant periods from the H/V spectral ratio for 14 seismic motions with respect to PGV, showed no convincing evidence of an increase in the predominant period with the motion intensity which indicates the absence of nonlinear soil behavior. The differences in amplitude between strong and weak-to-moderate ground motions could be due to differences in the incoming wavefield (e.g., incidence angle). Additionally, the very weak/weak motions are averaged over a large number of events, while the strong motions represent only a few events, which may also explain the differences between very weak to strong ground motions.

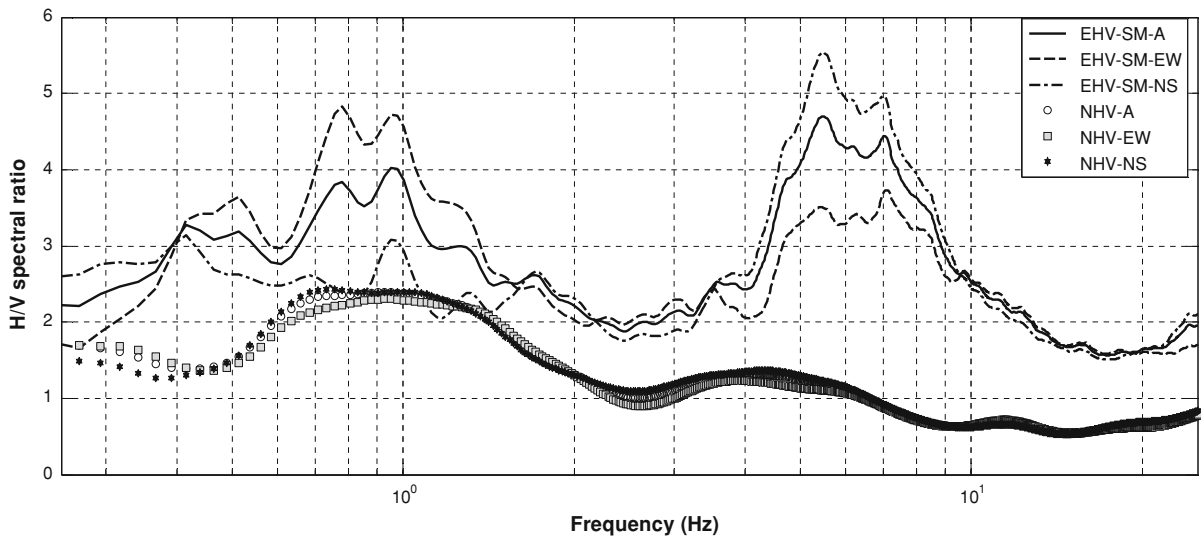


Figure 7

North–South, East–West and average H/V spectral ratios for strong motion (EHV) and microtremor (NHV) at Boumerdes site and directionality effect

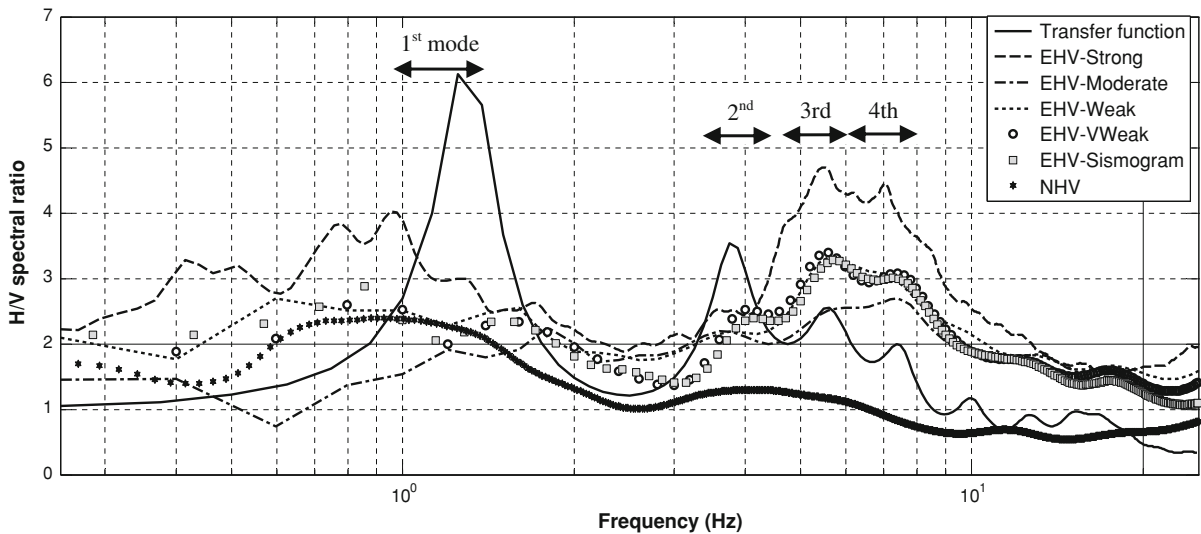


Figure 8

Comparison between the very weak to strong seismic motion H/V spectral ratios (EHV), and microtremor (NHV) with the transfer function at Boumerdes site

In Boumerdes city, the mainshock was particularly destructive with $EMS-98 = X$. Many constructions, mostly mid-rise reinforced concrete buildings (four and five stories) built after 1970 (Fig. 15), were destroyed, and many people were killed as a result of the collapse of buildings (MESLEM *et al.*, 2010). The plotted curves obtained for the Boumerdes station (Fig. 8), show a first common

peak around 0.8–1.2 Hz characterizing the resonant frequency f_0 . Important in the case of strong motions (Fig. 7), the amplitude of this peak is characterised by a smooth bump in the case of microtremor. This last result does agree well with recent published observations (GULLIER *et al.*, 2005; HELAL *et al.*, 2010) done in the Boumerdes area by performing microtremor measurements which show that a site



Figure 9
Typical damaged 4–5 story buildings in the Boumerdes area near the Boumerdes station (near source)

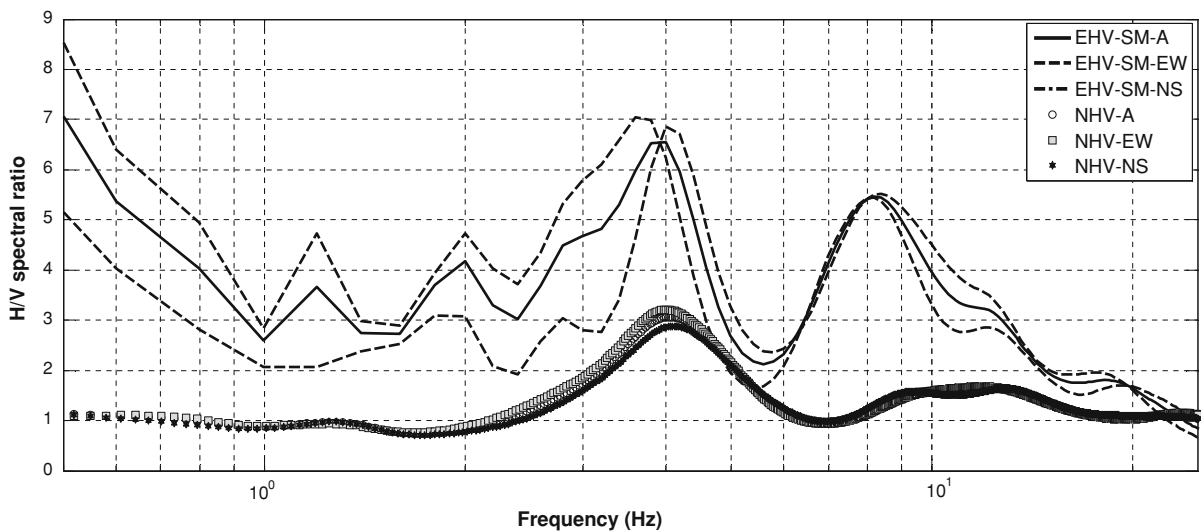


Figure 10
North–South, East–West and average H/V spectral ratios for strong motion (EHV_SM) and microtremor (NHV) at Dar el Beida site and directionality effect

effect is evidenced by a smooth bump at 0.8–2 Hz. This result suggests that the microtremors underestimate the H/V spectral ratio during earthquakes and shows that a bump identified by microtremor survey can hide a stronger amplification. Moreover, we note that the fundamental frequency evidenced by the transfer function is around 1.3 Hz (Fig. 8). The slight

difference with the EHV first peak is due certainly to the uncertainty on the sediment-halfspace interface depth. Higher common peaks are evidenced as well by the EHV as by the transfer function at 3.9, 5.5 and 7 Hz (Fig. 8) and are close to the peaks evidenced by the Fourier amplitude (Fig. 3). Those peaks which are not evidenced by the microtremor data may represent

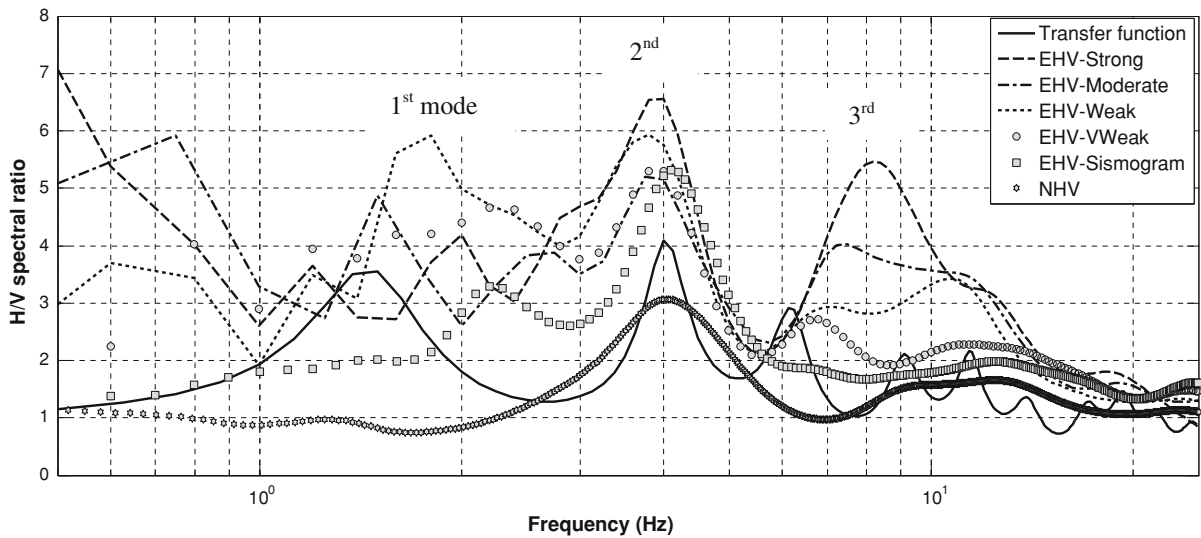


Figure 11

Comparison between the very weak to strong seismic motion H/V spectral ratios (EHV), microtremor (NHV) with the transfer function at Dar el Beida site

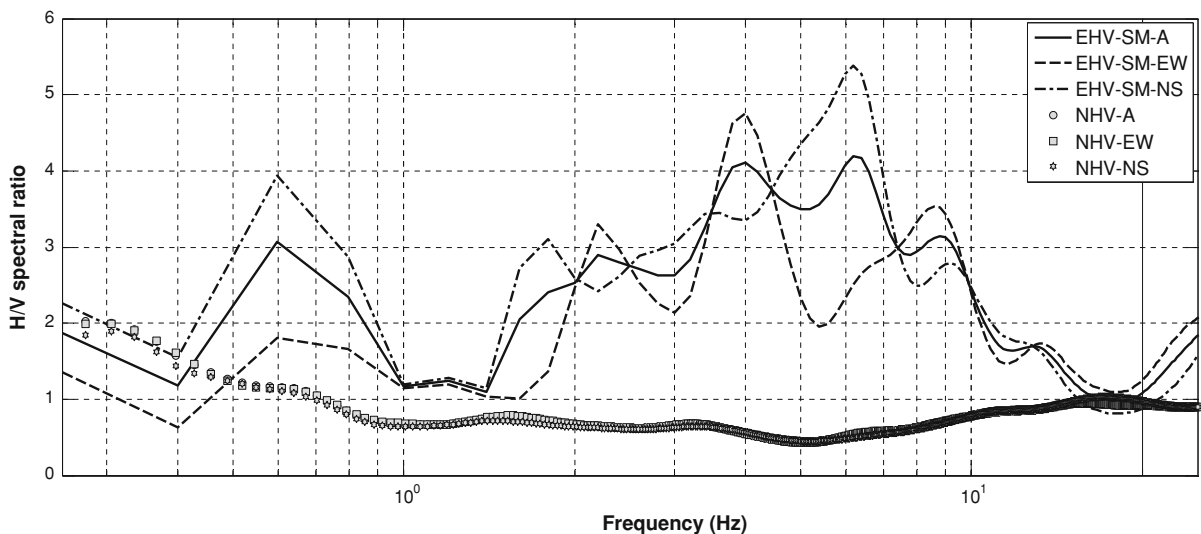


Figure 12

North–South, East–West and average H/V spectral ratios for strong motion (EHV_SM) and microtremor (NHV) at Hussein Dey site and directionality effect

higher modes regarding the plotted transfer function. Also, if we use the following simple 1-D model—1 equivalent layer modal frequency assumption:

$$f_n = (2n + 1)f_0, \tag{2}$$

where f_n is the n th mode frequency, and f_0 is the fundamental frequency equal to 1.2 Hz, one can remark that $f_1 = 3.6$, $f_2 = 6$ and $f_3 = 8.4$ are the first,

second and the third mode. The slight difference between Eq. 2 and the transfer function is related to the fact that this equation supposes a one layer profile while the transfer function is a two layers profile.

Considering that the great damage observed in the epicentral zone was mainly affecting 3–5 story buildings with fundamental frequencies between 4 and 6 Hz (DUNAND *et al.*, 2004), most damage in

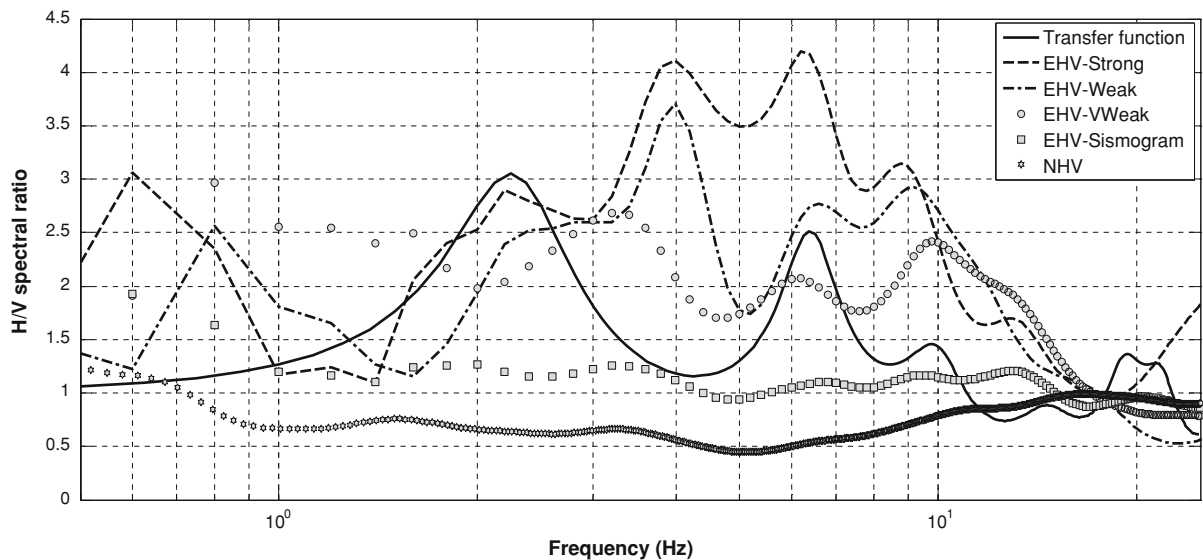


Figure 13

Comparison between the very weak to strong seismic motion average H/V spectral ratios (EHV), microtremor (NHV) with the transfer function at Hussein Dey site



Figure 14

Typical old apartment building: damage was typically concentrated around openings and the *top* suffered from the excessive displacement

Boumerdes (Fig. 15) can not be explained by the 0.8–2 Hz peak but more probably by the peaks between 3.9 and 5.5 Hz. Based only on microtremor measurements in the epicentral area, recent studies (GUILLIER *et al.*, 2005; HELLAL *et al.*, 2010) conclude that the observed great damage is not related to a site effect. This conclusion leads to ignoring any site effect in this area during the reconstruction; consequently, it is useful to be careful during the evaluation of the site effects based on microtremor

measurements only. Seismic motion “EHV” seems to be a useful tool to enhance the quantification of site effects during earthquakes. It should be noted that the true amplification may, ultimately, only be derived using site-to-reference spectral ratios. Also, we need further studies on other sites and other earthquakes in order to appreciate the uniqueness of the interpretation of higher modes associated with higher peaks.

According to the H/V spectral ratios curves (Fig. 10), the ground motion at Dar El-Beida station

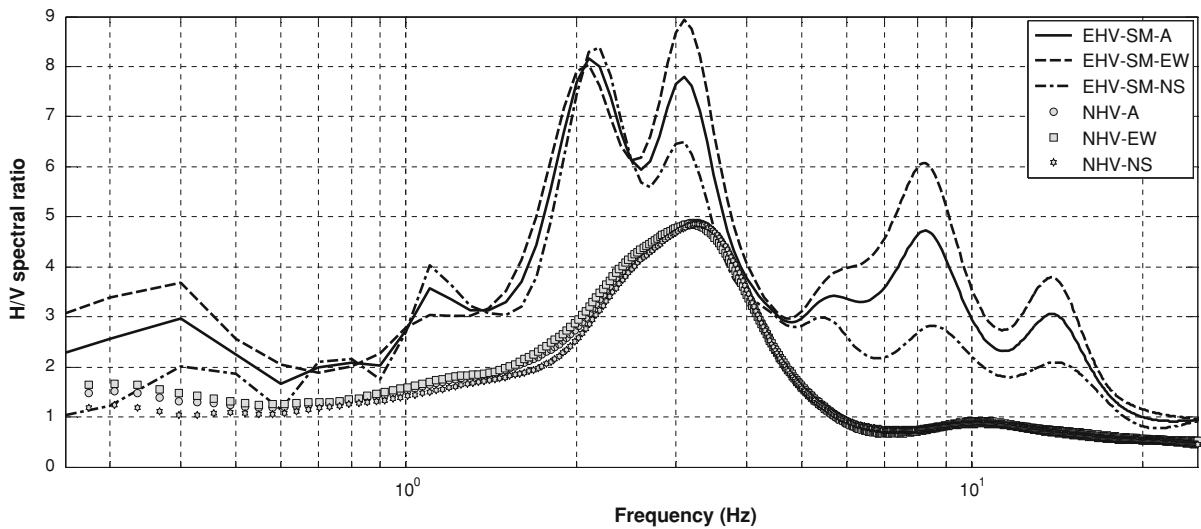


Figure 15

North–South, East–West and average H/V spectral ratios for strong motion (EHV_SM) and microtremor (NHV) at El Afroun site and directionality effect

has been strongly affected by the local soil conditions, with a remarkable common clear peak around 4 Hz in agreement with the quaternary soft deposits of the Mitidja basin where the station is located. This peak is identified as well by microtremor as by seismic motion and agrees well with the transfer function. The transfer function shows a lower peak around 1.5 Hz evidenced by the moderate and weak seismic motion. The available shear wave velocity profile is not derived from geophysical measures but estimated from existing engineering classification models for different geological units (JICA and CGS, 2006). A higher peak appears in the case of strong motion at a frequency of 8 Hz which is probably indicative of the influence of a thin surficial soft soil layer (GUEGUEN *et al.*, 2000; DELGADO *et al.*, 2002). According to Eq. 2, the first three mode frequencies are 1.5, 4.5 and 7.5 Hz which agree with the observed peaks, respectively, at 1.5, 4 and 8 Hz and with the Fourier amplitude evidenced peaks (Fig. 4). It should be pointed out that the modes 1–3 interpretation is not unique; the two peaks could just as well represent fundamental mode resonance frequencies of two impedance contrasts.

For Hussein Dey station (Fig. 12), the plotted curves don't show a clear peak and the amplitude from the transfer function as well as accelerometric, seismometric and microtremor motions is relatively

small, which denotes a firm or rock soil beneath the station. However, whereas the NHV and the EHV seismogram give a flat curve in agreement with a rock site characteristic, the strong motion EHV curves reveals four moderate peaks at frequencies 2.2, 4, 6.5 and 9.8 Hz. Whereas the 2.2, 6.5 and 9.8 Hz frequencies are well evidenced by the transfer function, it is not the case for the 4 Hz peak. According to the transfer function and to Eq. 2, it seems that the 2.2, 6.5 and 9.8 Hz peaks are, respectively, the fundamental, the second and the third mode frequencies. In this area, the heavy and rigid masonry buildings (Fig. 16) have suffered during the Boumerdes earthquake. The observed damage was typically concentrated around openings and the top from the excessive displacement. The fundamental frequencies of those rigid masonry buildings are around 4–6 Hz close to the observed higher soil modes.

According to the H/V spectral ratios curves, the ground motion at El Afroun station seems to have been strongly affected by the local soil conditions, with a remarkably common clear amplitude around 3 Hz in agreement with the quaternary soft deposits of the Mitidja basin where the station is located (Fig. 14). This peak is identified as well by microtremor as by strong and very weak seismic motion. A higher peak at around 8.5 Hz is evidenced by the

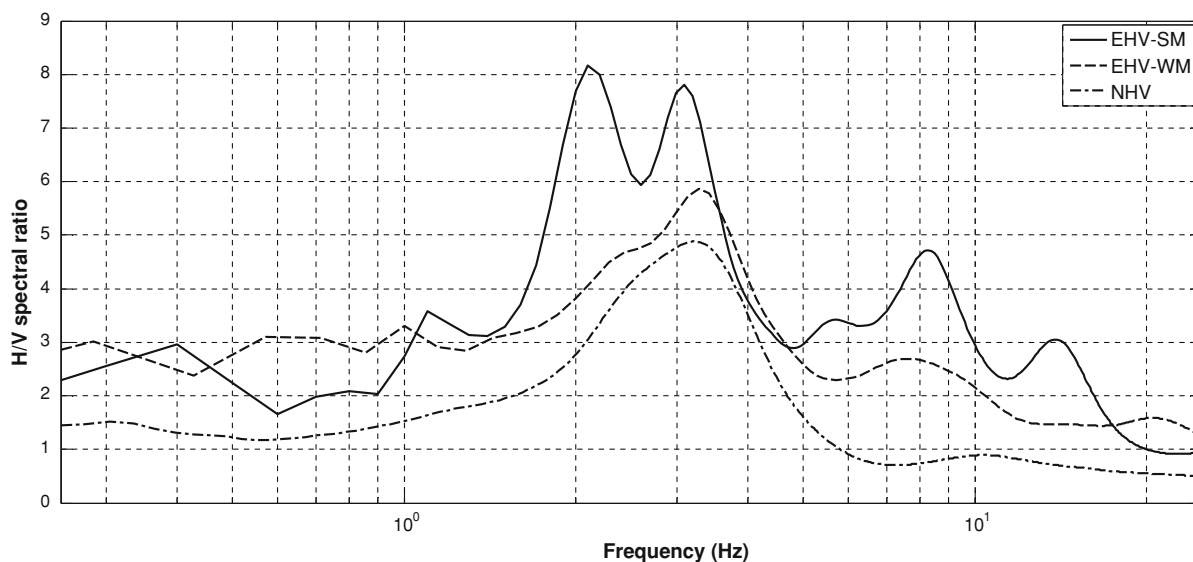


Figure 16

Comparison between very weak (EHV-VWM) and strong seismic motion (EHV-SM) H/V spectral ratios with microtremor (NHV) at El Afroun site

strong motion and slightly by the very weak motion. This peak which is not evidenced by the microtremor data represents probably a higher mode according to Eq. 2.

It is useful to underline that except for the El Afroun station located 86 km far from the Boumerdes main shock epicentre, the Boumerdes station, located in the epicentral area, the Dar el beida and Hussein Dey stations, located, respectively, at 29 and 36 km far from the epicentre, are all characterized by a relevant H/V spectral ratio amplitude for frequencies between 4 and 6 Hz. These frequencies, which do not correspond to the fundamental frequency, are indicative of the interest in analysing the higher frequency peaks which cannot be found when looking at noise NHV alone. This frequency range correlates well with the near field earthquake characteristics (LAOUAMI *et al.*, 2006) and with the most damaged buildings' fundamental frequencies around 4–6 Hz (DUNAND *et al.*, 2004). The obtained results show clearly that the observed damage in the studied regions can be related to site effect via the contribution of the high modes of soils. It should be pointed out that the higher modes interpretation is not unique; the peaks could just as well represent fundamental mode resonance frequencies of impedance contrasts.

4.3. EHV from Response Spectra

In this part we calculate the ratio EHV based on the accelerograms response spectra rather than on the accelerograms Fourier spectra. We follow the same procedure as in the previous methodology, the difference is that we use in the calculation of the pseudo response spectra a damping of 0.05 instead to smooth the obtained curve. From the plotted curves (Fig. 17), it results that the EHV from response spectra are similar to those obtained from Fourier spectra and the same peaks are evidenced. Moreover, the calculation of the response spectra is more easily compared with the smoothing operation of the Fourier spectra.

5. Conclusions

The Algiers–Boumerdes region is located close to a set of active faults. Most of its downtowns are built on thick soft sediment, which may significantly amplify the earthquake ground motion during events such as the Boumerdes earthquake.

In this study, we analyze earthquake-induced site effect from microtremors (NHV), seismograms, very weak, weak, moderate and strong (PGA >10 % g)

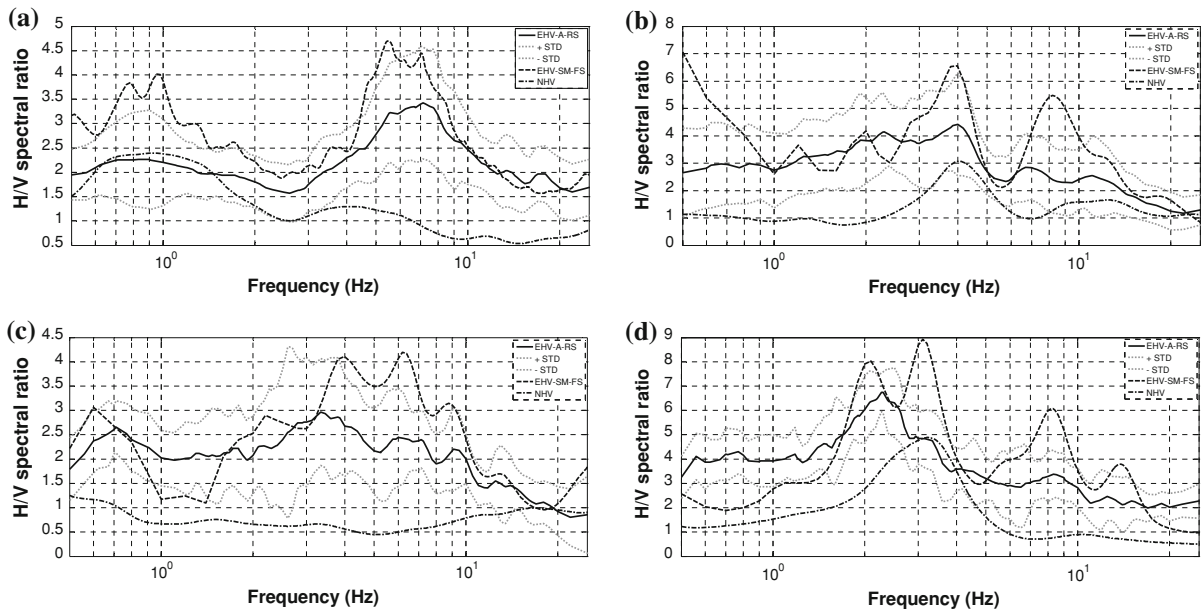


Figure 17

Comparison between the average EHV from response spectra (EHV-A-RS) + and – standard deviation with EHV strong motion from Fourier spectra (EHV-SM-FS) and microtremor (NHV) at **a** Boumerdes site, **b** Dar el Beida site, **c** Hussein dey site and **d** El Afroun site

motions (EHV), and transfer function evaluation from soil velocity profile data at four sites where the damage was most extensive. H/V spectral ratios are computed by using Fourier spectra and response spectra. In the Boumerdes epicentral region, two studies dealing only with microtremor measurements have been published and concerned with the epicentral area of the 2003 Boumerdes earthquake (GUILLIER *et al.*, 2005; HELLAL *et al.*, 2010). The NHV obtained results show only one peak identifying a resonance frequency which is not comparable with the building fundamental frequency. Their conclusion was that the observed great damages are not related to the site effect. However, the EHV shows other secondary peaks, comparable with the building fundamental frequency, with a stronger H/V spectral ratio which could be related to the soil higher modes. Our analysis deals with site effect based on the recorded seismic motion spectral ratio and we focus on the identification of higher peaks, their relation with the soil higher modes and their correlation with the observed damage during the may 21st 2003 Boumerdes earthquake ($M_w = 6.8$). Additionally, we analyse the directionality effect on the earthquake horizontal to vertical spectral ratio (EHV).

Compared to the transfer function, the obtained results show that, NHV as well as EHV give a good estimation of the soil fundamental frequency, whereas the NHV provide a lower bound in amplitude. Moreover, the EHV amplitude increases with the seismic motion intensity and reveals strong amplitude at frequencies higher than the fundamental one. The differences in amplification between strong and weak-to-moderate ground motions could be due to differences in the incoming wavefield (e.g., incidence angle). In the case of firm soils, whereas the NHV gives a flat curves synonym of a rock site or a bump, the EHV is more appropriate by identifying nonnegligible H/V amplitude. With regard to the contribution of the higher peaks revealed by EHV curves, the comparison of the EHV curves with the computed transfer function as well as with analytical 1D-1Layer frequency formula identifies high modes with relevant amplitude. Those modes are in agreement with the distribution of damage during the M_w 6.8, 2003, Boumerdes earthquake. The Boumerdes station, located in the epicentral area, the Dar el Beida and the Hussein Dey stations, located, respectively, at 29 and 36 km far from the epicentre, are all characterized by the relevant H/V spectral

ratio for frequencies between 4 and 6 Hz. These frequencies, which do not correspond to the fundamental frequency, are indicative of the interest of analysing the higher peaks in the case of earthquakes which cannot be found when looking at noise NHV alone. This frequency range correlates well with the near field earthquake characteristics and with the most damaged buildings' fundamental frequencies. The obtained results show that the observed damages in the studied regions can be related to site effect via the contribution of the high modes of soils. It should be pointed out that the higher modes interpretation is not unique; the peaks could just as well represent fundamental mode resonance frequencies of impedance contrasts.

Consequently, it is useful to be careful during the evaluation of the site effects based on microtremor measurements only. Seismic motion EHV seems to be a useful tool to enhance the quantification of site effects during earthquakes.

Finally, the same analysis is performed by using response spectra rather than Fourier spectra and leads to the same results. Moreover, the calculation of the response spectra is more easily compared with the smoothing operation of the Fourier spectra.

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