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SITE EFFECTS ESTIMATION USING EARTHQUAKE AND AMBIENT NOISE DATA: THE CASE OF LEFKAS TOWN (W. GREECE)

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SUMMARY

The town of Lefkas is assigned zone III in the current Greek seismic code and has been repeatedly hit in the past by strong nearby earthquakes, the last one occurring on 14 August 2003 (M6.2). An accelerograph, installed almost thirty years ago in the town of Lefkas, recorded the mainshock with a PGA≈0.42g. After this strong earthquake, four digital, high-resolution accelerographs were installed at selected soil sites of the town and one at a reference "rock" site. During three months of continuous operation, this array recorded several hundreds of aftershocks, providing a large dataset suitable for site effects study in the town of Lefkas. This dataset consists mainly of low-amplitude recordings (PGA<0.05g) and represents the weak-motion dataset. At the aforementioned strong-motion station sites, single-station ambient-noise measurements were performed using a broadband sensor with a high-resolution digitiser. These measurements constitute the ambient-noise dataset. We processed the recordings from both datasets by applying the SESAME-software and a common procedure. First, at all soil sites we evaluated the standard spectral ratio (SSR) and horizontal to vertical component spectral ratio - the so called receiver function (RF) - using the weak motion dataset. Then we used ambient-noise data to estimate HVSR at all stations. Comparison between SSR and RF ratios for earthquake recordings reveals similarity in the evaluated fundamental frequencies but striking differences in their amplitudes, in agreement with previous results. At one soil site the mainshock strong-motion RF is found to be shifted to lower frequencies with respect to weak-motion and ambient-noise ones, indicating non-linear behavior of the corresponding soil materials. An attempt is made to explain the obtained experimental results with 1D modeling.

1. INTRODUCTION

Experimental site effects studies are of high importance to microzonation and land use planning in urban areas. In regions of moderate to high seismicity seismic recordings are easily acquired following a mainshock in the vicinity of a residential area by deploying a strong motion network of high resolution recorders. Various techniques are used to better confine the site effects throughout the study area depending on the available number of instruments.

The best procedure for determining the site response of a particular sedimentary location is to record ground motion during an earthquake and calculate the spectral ratio of the sediment site recording to a nearby reference site located on rock (e.g. Borcherdt, 1970). However, to gather sufficient data using this technique in a reasonable period of time may be difficult, especially in regions of low seismicity. On the other hand, the numerical prediction of site effects with a reasonable confidence level requires a detailed knowledge of some key geotechnical and geophysical parameters, which is also a difficult task.

An alternative approach to characterizing site response in urban environment involves the use of the H/V

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spectral ratio of earthquake and ambient noise recordings. Ambient noise is low amplitude vibrations of soilgenerated by natural disturbances such as wind, sea tides or of manmade origin such as traffic, industrial machinery, household appliances etc. The spectral ratio of horizontal to vertical component of ambient noise usually shows a peak indicating the fundamental frequency of the investigated site (Nogoshi and Igarashi, 1971; Nakamura, 1989). During the last two decades a lot of research efforts have been dedicated to site effects studies using both earthquake and ambient noise data and testing their reliability (among others; Lachet et al. 1996, Mucciarelli 1998, Bard 1999, Horike et al. 2001, Satoh et al. 2001). Furthermore, several researchers (among which Field and Jacob, 1993; Lachet and Bard, 1994; Lermo and Chávez-García, 1994, Bonnefoy-Claudet et al., 2004) have theoretically supported the H/V spectral ratio technique through numerical simulations showing that synthetics obtained by randomly distributed near-surface sources lead to H/V spectral ratios sharply peaked around the fundamental S-wave frequency whenever the surface layers exhibit a sharp impedance contrast with the underlying stiffer formations.

In this paper, experimental site effects for selected sites of the town of Lefkas are studied using earthquake aftershock recordings and ambient noise data. For this purpose, both standard spectral ratio and horizontal-to-vertical spectral ratio techniques are used. Comparison of the results stemming from the aforementioned techniques exhibits similarities as well as discrepancies in the examined frequency range and corresponding amplitudes. Results from 1D modelling for one site satisfactorily explains the experimental transfer functions.

2. DATA AND METHOD USED

2.1 Earthquake recordings and ambient noise data

On August 14, 2003 at 05:14 GMT, a strong earthquake with magnitude M=6.2 occurred close to the island of Lefkas in western Greece (Fig. 1). The earthquake was strongly felt in the Ionian islands (Cephalonia, Zakynthos, Ithaki, etc.) as well as on the mainland of Greece. The epicenter was located in the Ionian Sea, about 12km southwest of the town of Lefkas (Karakostas et al., 2004).

Within a few days after the mainshock the Institute of Engineering Seismology and Earthquake Engineering (ITSAK) deployed a temporary network of nine digital accelerographs of high resolution in the broader epicentral area, aiming at investigating strong ground motion distribution and identifying possible site effects (ITSAK & NTU Report, 2003). Of these stations, four were installed in the town of Lefkas (LDD: Forest Directorate, LHS: Hospital, LTH: Town Hall, LMA: Port-Marina) and one (LMF) near the Monastery of Faneromeni (Fig. 1). Fig. 2 shows the recordings of an aftershock of the 21 August 2003, 00:07GMT event coming from all five stations of the temporary network deployed in the town of Lefkas. The shorter duration of the horizontal component, the lower amplitudes and higher frequency content observed at the LMF reference station with respect to the rest of the stations installed on recent alluvium is obvious. This is an additional indication that LMF serves satisfactorily as a reference station in the SSR method.

From the total temporary network recordings, a data set of 38 events was selected for the period August 20 to September 30, 2003. Although all examined events fall in the seismogenic area only for 20 of them seismological parameters are available (Table 1). These shocks, with magnitude between 3.3 and 4.2, occurred in an area extending from the southwest to the northern part of the island. 213 horizontal components were used to apply the SSR method and 221 horizontal and 111 vertical components to apply the RF method. Number of data used for each method and station are given in Table 2.

The LMF station is underlain by limestone and was for this reason selected as the reference station. The remaining four stations were installed on recent alluvium deposits that underlay almost the whole town of Lefkas (IGME, 1963). An average geotechnical profile representative of the central part of the town of Lefkas, around the LHS station, proposed by Theodulidis and Tsakalidis (1994) and slightly modified by Dimitriu et al. (1999), is given in Table 3.

Ambient noise measurements with 30minutes duration were performed at all nine accelerometric stations of the temporary network during the calm hours of the day using a high resolution 24-bits digitizer and a broadband sensor with a sample rate of 100 Hz. The response of the seismometer is flat between 0.2 and 50 Hz (combination of CityShark recorder with Lenartz 5s/3D sensor). Ambient noise measurements were performed according to the guidelines of the SESAME European project, (2004) (Chatelain et al., 2000, Atakan et al., 2004; Duval et al., 2004, Koller et al., 2004).

Table 1: Information on the aftershocks used in this study.

YEAR	*MONTH*	*DATE*	*HOUR*	*M*	*LATITUDE*	*LONGITUDE*	*Data Source*
2003	Aug	20	13:31:00.00	-	38.821	20.614	*AUTh*[1]
2003	Aug	20	18:12:00.00	-	38.773	20.590	*AUTh*
2003	Aug	20	20:03:03.00	-	-	-	-
2003	Aug	21	00:07:39.89	4.2[2]	38.802	20.603	*AUTh&UPatras*
2003	Aug	21	05:18:42.74	4.2[2]	38.665	20.555	*AUTh&UPatras*
2003	Aug	21	09:58:42.30	3.9	38.760	20.595	*AUTh*
2003	Aug	21	20:19:40.00	-	-	-	-
2003	Aug	21	21:23:49.00	-	-	-	-
2003	Sep	03	06:33:25.59	3.7	38.847	20.626	*UPatras*[2]
2003	Sep	05	19:21:30.00	-	-	-	-
2003	Sep	06	06:57:18.46	3.5	38.748	20.650	*UPatras*
2003	Sep	06	08:59:53.71	3.5	38.753	20.636	*UPatras*
2003	Sep	06	20:28:20.51	3.5	38.759	20.638	*UPatras*
2003	Sep	07	19:51:00.00	-	-	-	-
2003	Sep	08	18:32:28.00	-	-	-	-
2003	Sep	08	23:51:00.00	-	-	-	-
2003	Sep	10	09:45:20.00	-	-	-	-
2003	Sep	11	20:09:09.50	-	-	-	-
2003	Sep	12	23:41:15.00	-	-	-	-
2003	Sep	12	23:58:26.00	-	-	-	-
2003	Sep	13	04:14:07.80	3.8	38.801	20.749	*UPatras*
2003	Sep	13	06:44:44.20	3.6	38.810	20.774	*UPatras*
2003	Sep	14	07:44:44.40	3.6	38.686	20.607	*UPatras*
2003	Sep	14	10:42:00.38	3.3	38.791	20.728	*UPatras*
2003	Sep	14	13:10:54.00	-	-	-	-
2003	Sep	14	17:00:08.00	-	-	-	-
2003	Sep	15	06:50:05.00	-	-	-	-
2003	Sep	15	08:48:30.00	-	-	-	-
2003	Sep	15	19:40:00.00	-	-	-	-
2003	Sep	19	12:31:08.01	3.5	38.728	20.724	*UPatras*
2003	Sep	20	00:14:19.76	4.0	38.720	20.391	*UPatras*
2003	Sep	23	01:23:29.80	3.7	38.617	20.408	*UPatras*
2003	Sep	23	20:25:12.00	-	-	-	-
2003	Sep	24	04:43:29.00	-	-	-	-
2003	Sep	28	15:29:26.34	4.2	38.928	20.710	*UPatras*
2003	Sep	29	12:59:09.43	3.7	38.769	20.698	*UPatras*
2003	Sep	29	00:44:20.15	3.6	38.619	21.126	*UPatras*
2003	Sep	30	05:56:32.63	4.1	38.658	20.563	*UPatras*

Table 2. Number of recordings (horizontal components) used in the analysis.

Station Code	LMF	LDD	LTH	LMA	LHS
Method SSR	50	44	50	19	50
Method RF	50	46	52	19	54

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1 → AUTh: Aristotle University of Thessaloniki
2 → UPatras: University of Patras

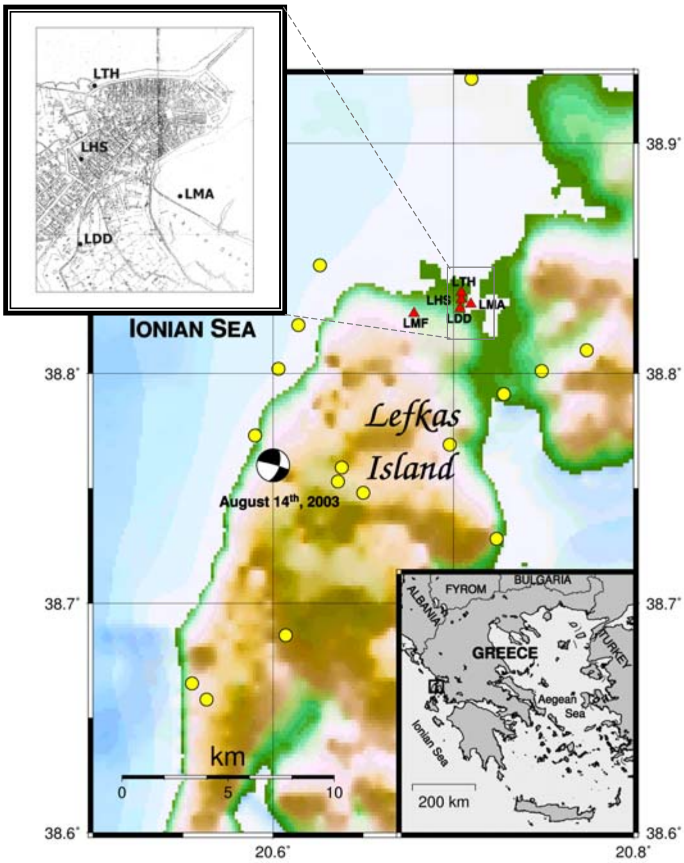

Figure 1: Map indicating aftershocks (yellow circles) and mainshock (focal mechanism balloon) epicentres. Accelerometric stations deployed within and close by the Lefkas town are shown by triangles.

Table 3. Site structure underlain the centre of Lefkas town, in the vicinity of the LHS station (adapted from Theodulidis and Tsakalidis, 1994 & Dimitriu et al. 1999). In the linear 1D modelling, two extreme values of the layer 1, Vs=100 and 70m/s were used.

	Geologic description	Thickness (m)	Density (kg/m^3)	Vs (m/s)	Qs	Vp (m/s)	Qp
Layer 1	sandy silt	8	1900	100	17	170	30
Layer 1-modified	sandy silt	8	1900	70	10	170	30
Half space	marl	∞	2200	600	50	1080	120

2.2 Processing method

To homogeneously process earthquake and ambient noise data, we applied the JSESAME software modules (SESAME European project, 2004) all three methods, that is SSR, RF and HVSR. For earthquakes, the entire recording length was taken, ranging from about 10sec to 60sec. For ambient noise recordings, a number of windows having a duration of 60 sec each was selected using the 'manual window selection' module of the JSESAME software.

The following steps were applied toall data used: (a) offset correction, (b) computation of Fourier spectra in all three components (E–W, N–S, UP), (c) application of a cosine taper, (d) smoothing of the Fourier amplitude spectra by a Konno-Ohmachi algorithm (Konno and Ohmachi, 1998). Data analysis was focused in the frequency range between 0.2 and 20 Hz. For each discrete frequency point the horizontal recording spectrum was divided by the vertical one, separately for both horizontal components for the RF and HVSR method; for the SSR method, NS and EW horizontal components of the 'alluvium' stations were separately divided by the corresponding ones of the reference station LMF. Thus, for all three methods of analysis, a common procedure was implemented so that any similarities or differences observed could be attributed to factors other than data processing itself.

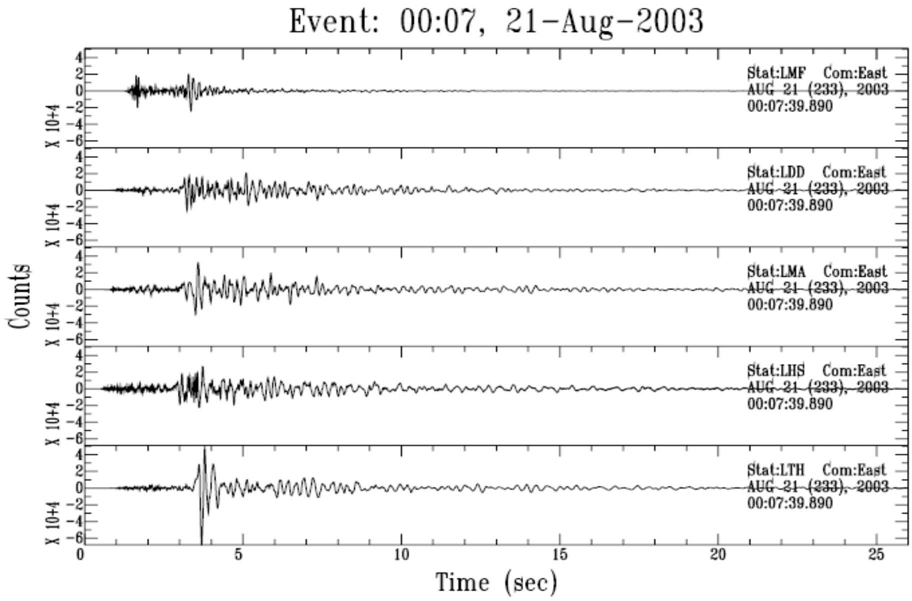

Figure 2: Recordings of an aftershock in all stations of the aftershock network (LMF: Reference station).

3. RESULTS

In Fig. 3 results of the SSR method are shown for four alluvium stations LDD, LHS, LTH, LMA. For all of them an amplification 'bump' with amplitude greater than 2 is observed for the frequency range between 0.4Hz and about 10Hz. For mean standard spectral ratio amplification factors (SSR_AF) greater than 5, the frequency range is restricted to 1.5Hz and 5Hz, with a mean for each station SSR_AF_{LTH}~11, SSR_AF_{LMA}~8, SSR_AF_{LHS}~7.5 and SSR_AF_{LDD}~5.5.

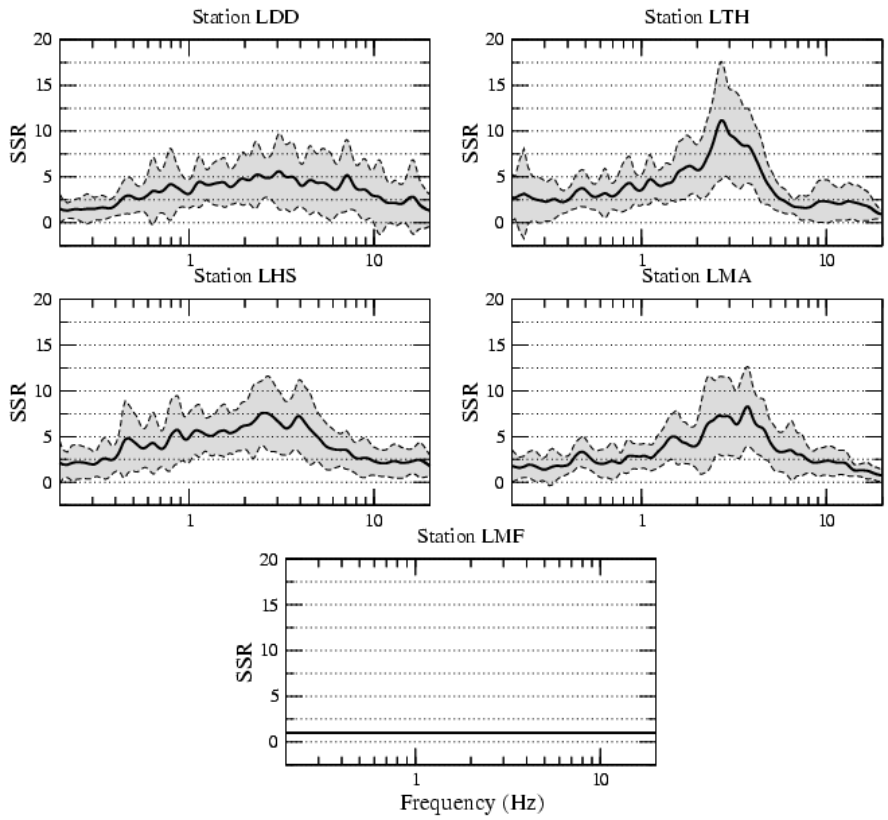

Figure 3: Mean standard spectral ratios (SSR) ± one standard deviation from aftershock recordings.

In Fig. 4 results from the RF method are shown for all five stations: LDD, LHS, LTH, LMA and LMF. For all alluvium stations an amplification 'bump' with amplitude greater than 2 is observed for the frequency range between 0.4Hz and about 5Hz. For the reference station LMF such a 'bump' is observed in a narrow frequency range between 0.7Hz and 1.4Hz with amplification less than 3. However, mean receiver function amplification factors (RF_AF) greater than 5 are observed only for stations RF_AF_{LTH}~6 and RF_AF_{LMA}~5 for a narrow frequency range 2Hz to 4Hz and 3Hz to 3.5Hz, respectively. The RF of the mainshock recording at the Hospital [LHS] is also plotted in Fig. 4. It is evident that RF of both horizontal components is shifted in lower frequencies between 1.5Hz and 2.0Hz with high amplification$10 \leq RF_AF_{LHS} \leq 12$. In addition, in one horizontal component a sharp peak with RF_AF~7 appears around 0.4Hz.

In Fig. 5 results are shown from the HVSR method applied to ambient noise measurements, from all five stations: LDD, LHS, LTH, LMA and LMF. Horizontal-to-vertical amplification factor (HVSR_AF) is marginally higher than 2 for all alluvium stations. More specifically, it is observed that $HVSR\_AF_{LDD}>2$ between 0.35Hz and 0.6Hz, $HVSR\_AF_{LHS}>2$ between around 0.4Hz, $HVSR\_AF_{LTH}>2$ around 0.4Hz as well as between 1.5Hz and 3.0Hz, $HVSR\_AF_{LMA}>2$ between 1.5Hz and 2.5Hz. For the reference station, it is observed that $HVSR\_AF_{LMF}<2$ for all frequencies examined.

Mean SSR, RF and HVSR ratios are plotted for all stations in Fig. 6. It is observed that spectral shapes of SSR and RF are quite similar with values of AF_SSR, being 2 to 3 times higher than those of AF_RF. However, amplification factor AF_HVSR clearly deviates from AF_RF for frequencies greater than about 1.0Hz to 1.5Hz, for all alluvium stations. For station LMF although RF shows higher amplification than HVSR for almost all frequency range examined, spectral shapes are comparable. It seems that for examined alluvium sites of Lefkas the experimental HVSR based on ambient noise do not show a clear fundamental frequency that would, on one hand, fulfill the SESAME guidelines and on the other would exhibit similar spectral shapes with those of the RF method. The main difference between these two spectral ratios stems from the excitation source type being seismic source for the RF and ambient noise sources for the HVSR. Although one could expect satisfactory excitation level from ambient noise sources for frequencies greater than 1.5Hz, capable to exhibit any fundamental frequency beyond it, it seems that either fundamental frequency lies in low frequency range <1.0Hz or the ambient noise vertical component is preferentially enriched with high frequencies with respect to the horizontal ones. In low frequencies, <1.0Hz, corresponding HVSR_AF is equal or lower than corresponding RF_AF.

4. DISCUSSION AND CONCLUSIONS

In this study, recordings from 38 earthquakes of the Lefkas 14/8/2003 aftershock sequence are used to estimate SSR and RF spectral ratios at selected sites of the Lefkas town. Aftershock epicentral distances vary between 5km to about 30km and magnitudes $3.3 \leq M \leq 4.2$. Ambient noise records acquired at the same sites are also used to estimate HVSR. All spectral ratios calculated using JSESAME's software modules (SESAME European prj., 2004), following thus a homogeneous processing procedure. The examined frequency band ranges between 0.2Hz to 20Hz.

SSR values for all alluvium stations showed a wide amplification band (0.4Hz to about 10Hz). However, a prominent central peak amplification is apparent in a narrow band between 2.5Hz to 3.0Hz, with amplification factors higher than 5 for the stations LTH, LMA and LHS. The station LDD shows slightly lower amplification factors than the latter ones (Fig. 3).

RF values for all alluvium stations exhibit a quite similar spectral 'shape' with the corresponding SSR ones but with a systematically 2 to 3 times lower amplification factor for almost entire frequency range. Even in this case, a central peak amplification is apparent in a narrow band between 2.0Hz to 4.0Hz, with amplification factors higher than 3 for the stations LTH, LMA and LHS. The station LDD shows amplification factors slightly higher than 3 at frequencies around 0.6Hz and 4.5Hz. Finally, for station LMF amplification factors do not exceed 3 for entire frequency range (Fig. 4). The shift of the mainshock RF to frequencies between 1.5Hz and 2.0Hz at the station LHS is in agreement with the previously observed shift in horizontal-to-vertical spectral ratio, attributed to soil non-linearity (Theodulidis and Bard, 1995, Dimitriu et al., 1999, 2000).

HVSR values do not show any clear peak for all alluvium stations, representing a case of almost flat ratio on sediments (Fig. 5). However, for frequencies lower than 1.5Hz a similarity between HVSR and RF values is observed. To better understand the nature of ambient noise recorded in the Lefkas town and explain any inability to show a clear fundamental frequency peak, further theoretical modelling is needed.

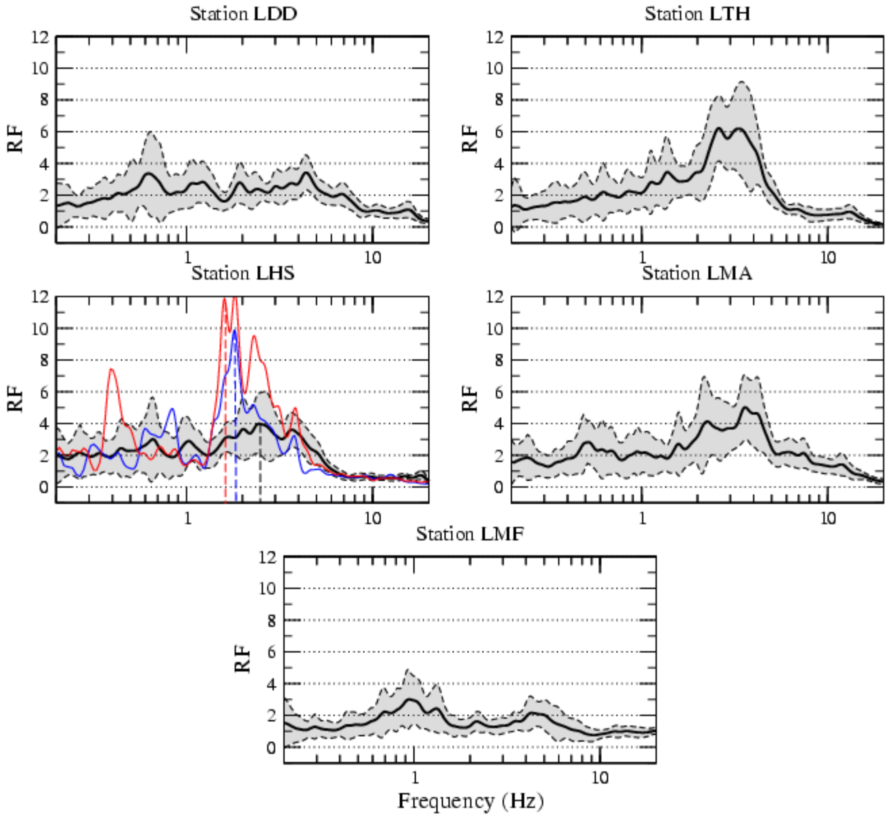

Figure 4: Mean horizontal-to-vertical (Receiver Function: RF) ± 1 standard deviation from aftershock recordings. RF of the mainshock for both horizontal components is also shown (red, blue lines).

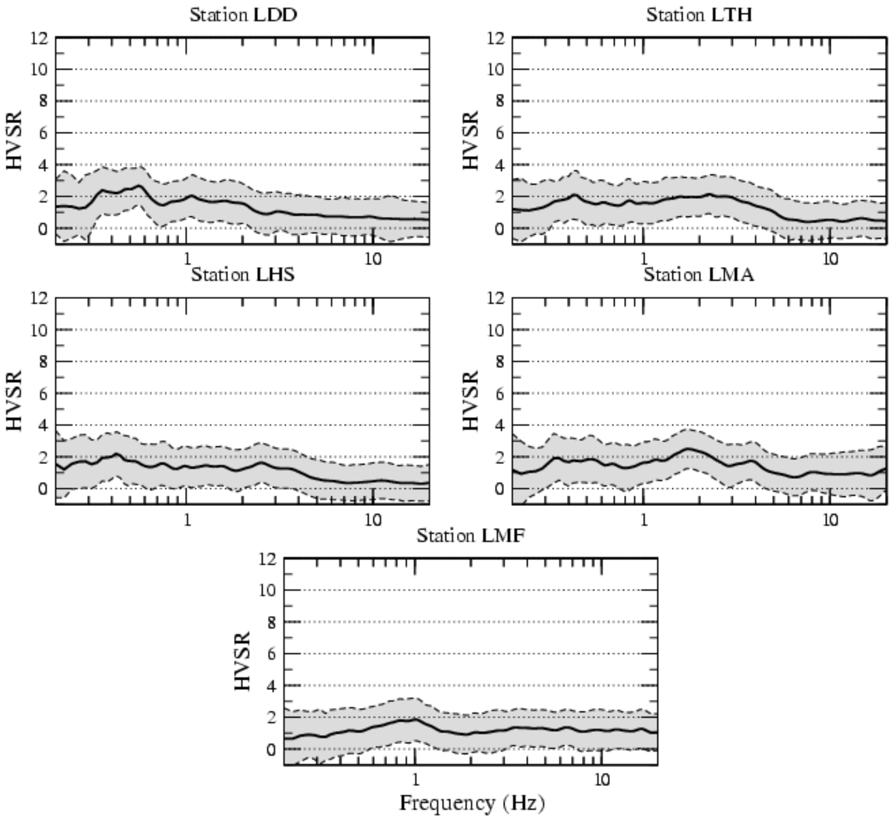

Figure 5: Mean horizontal-to-vertical spectral ratio (HVSR) ± 1 standard deviation from ambient noise recordings.

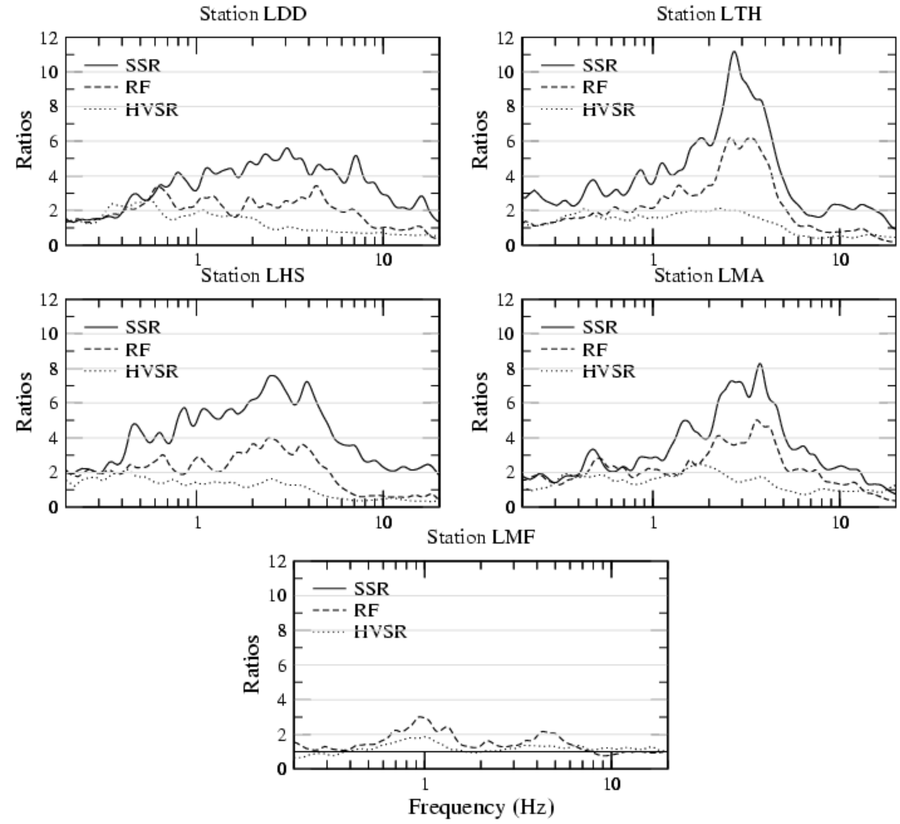

Figure 6: Mean ratios for the stations of the aftershock network.

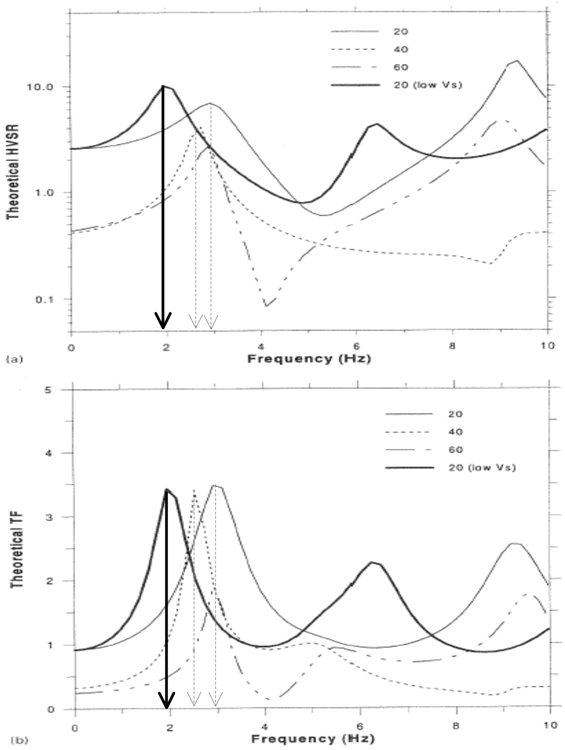

Figure 7: Theoretical SV-wave modelling of (a) HVSR and (b) TF [relative to bedrock outcrop] for the site structures of Table 4. Thin lines : soilwith Vs=100m/s and incidence at the layer-halfspace interface at 20^o (continuous lines), 40^o (dashed lines) and 60^o (dashed-dotted lines) from the vertical. Thick lines: soil with Vs=70m/s and incidence at 20^o. ***[Fig. adapted from Dimitriu et al. 1999].***

Results of 1D modelling based on the site structure of Table 3, adapted from Dimitriu et al. (1999) and presented in Fig. 7. Theoretical horizontal-to-vertical spectral ratios considering only an obliquely incident P or SV waves incident to an arbitrary angle show a fundamental frequency between 2.5Hz and 3.0Hz, in satisfactory agreement with the observed RF (Fig. 4). Theoretical transfer functions defined as the free-surface motion of the layered sediments versus the free-surface motion at the bedrock outcrop and considering P, SV or SH waves incident at an arbitrary angle also show a fundamental frequency between 2.5Hz and 3.0Hz. The latter is in good agreement with the observed narrow band between 2.5Hz to 3.0Hz in SSRs (Fig. 3).

The non-linear phenomena on RF spectral ratio have been observed and pointed out in several studies (Theodulidis and Bard, 1995, Dimitriu et al., 1999, 2000). Our results based on the Lefkas mainshock recording (Fig. 4) do support the idea that non-linearity could affect the horizontal-to-vertical spectral ratio, indicating the nature and extent of the non-linear effects.

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