Determination of Site Response in Lefkada Town (W. Greece) by Ambient Vibration Measurements

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Introduction

Lefkada together with the nearby Ithaki, Cephalonia, and Zakynthos islands are considered the most active areas of shallow seismicity in the Aegean Sea and the surrounding continental area. The region is dominated by the activity of the Cephalonia transform fault which comprises two distinctive fault segments (Louvari et al., 1999), the Lefkada segment to the north and the Cephalonia segment to the south. During instrumental times Lefkada Island has suffered from several earthquakes with magnitudes in the range 6.0-6.5. These events caused similar geotechnical damage consisting of rock fall, massive landslides, liquefaction, lateral spreading, and harbor quay wall failures (Benetatos et al., 2007). The hazard due to this fault system was updated to a peak ground acceleration of 0.36g in the current Greek Antiseismic Code. However, site-effects may increase the response beyond the provisions of local Codes or Standards. Especially in urban areas, like the Lefkada town, which is located on soft soil layer, waves of seismic events can be major amplified. That was the case during the 14 August 2003 Lefkada earthquake (Mw=6.2) which caused extremely high PGA=0.42g in Lefkada exceeding the PGA Standards. It is therefore strongly recommend determining possible site-effects and furthermore enforcing the proposed microzonation of Lefkada town to enhance the standard of seismic hazard analysis.

The analysis of ambient seismic vibration recordings for site effect estimation is considered a low-cost alternative to expensive investigation methods such as drilling or active seismic experiments. This study presents results of ambient noise measurements carried out in 78 locations in the town of Lefkada. The horizontal-to-vertical spectral ratios (Nakamura 1989) of ambient noise were used to approximate the fundamental resonance frequencies of the subsurface and their associated amplitudes. Summarizing the experiences of different authors with respect to ambient vibration processing, we selected transient free time windows for further analysis. Additionally, we calculated the site responses with respect to the reference site and compared the results with those obtained from the H/V technique. The fundamental frequency and the corresponding amplification factor were calculated for each site. Under the assumption that the H/V spectral ratios of ambient noise coincide with the amplification levels at the dominant frequency of the site response functions, the fundamental frequencies (f_0) and amplification factors (A_0) were compiled on ARC-INFO GIS software and corresponding maps were developed.

Materials and methods

Short geological description of the investigated area

Lefkada Island is separated from the Greek mainland by the Lefkada Sound, a shallow lagoonal environment. Lefkada town lies at the north-eastern corner of Lefkada Island at around 1-5 m above present mean sea level. It is situated on low resistance and rigidity

Holocene deposits of a few meters thick. They consist of alluvial and lagoon deposits, i.e. alternating soft clay, sometimes with organic content and sand-silt layers overlying a stiff marl formation (Gazetas et al., 2004). It should be noted that the quasi-uniform geological settlement of the neighboring area denotes that the whole town of Lefkada is predominantly characterized by similar formations of almost horizontal layering. The soil structure beneath the town is classified as category C according to the current Greek Antiseismic Code. On the basis of existing geological information (Gazetas et al., 2004), the top of the stiff marl formation is located at 9 m depth at northern Lefkada, at 16 m at the central town while it emerges southern in the area of Lygia harbor. This configuration implies for the presence of a geological trough. The stiff marl formation was found in all geotechnical depth profiles conducted by Gazetas et al., (2004), but its thickness is still unknown. Therefore the marl formation can be likely considered as typical “seismic bedrock” of Lefkada town. That means that seismic noise at all sites in the town encompass commonly the marl formation.

Ambient noise monitoring in Lefkada town

The investigated area was covered by seismic stations, each section comprising a discrete measurement site as shown in Figure 1. A total of 78 measurements were performed in October 2007 by two research groups, during daytime. The acquisition equipment included: 24-bit REFTEK 72A 3-channel digitizer, GPS (for timing and positioning), 3-component Guralp CMG40T sensor with a natural frequency of 1.0 Hz, portable PC. Digital recordings were made with a sampling rate of 100 samples per second. The duration of each 3-component recording was at least 20 minutes. The sensors were installed on soil conditions and sheltered in order to decrease weather and atmospheric disturbances. All the equipment – sensor, recorder, portable computer and connectors – were transported either by car or a trailer which served as the recording centres. Throughout the measurements the guidelines developed for ambient vibration measurements by the EU funded project SESAME (SESAME Guidelines 2004), were adhered to. At each location field measurements sheet was filled in which described the time, date, operator name, coordinates etc of the location the onset and the duration of the measurement. As reference site we selected Katouna village, situated ~5 km south of Lefkada town on stiff marl formations and performed a 36 hours continuous recording.

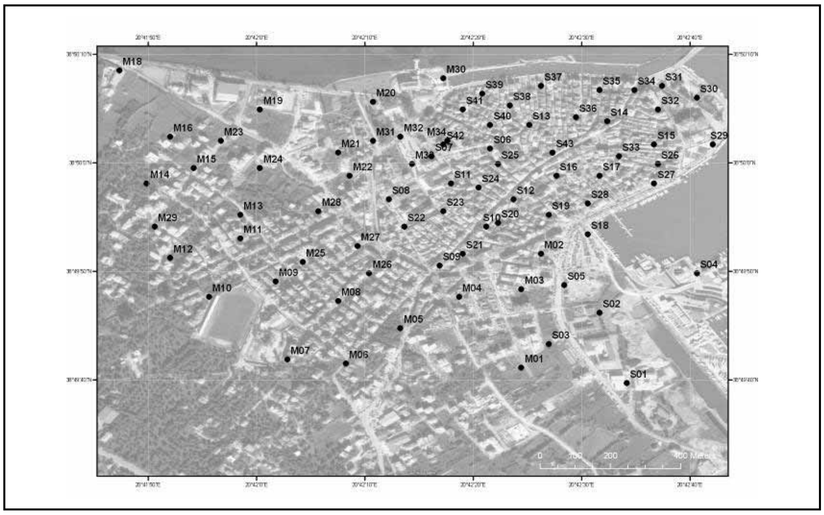

Figure 1. Satellite map of the study area and locations of the observation points.

Ambient noise H/V analysis

Data were processed applying the horizontal–to vertical (H/V) spectral ratio (Nakamura, 1989) method, using the GEOPSY software. The fundamental frequency (f_0) was calculated for each point. The H/V spectral ratios are those of selected time windows of recorded ambient noise using an anti-triggering algorithm. The selected time windows were Fourier transformed, using cosine-tapering before transformation and then smoothed following Konno & Ohmachi (1998) approach. The selected and analyzed time windows were 20 s long. We did, however, experiment with a range of values in order to find the window length that yielded satisfactory resolution of the peak being studied but was still stable in the frequency. After several tests, we concluded that a 20 s window provides stable results. The selected time window was free from recordings of passing vehicles, noticeable harmonic noise from nearby machinery, spiky data and other transient signals. All the selected time windows of each time series were corrected for the base line. The Fourier spectra were calculated for all segments using the Fast Fourier Transform (FFT). The Fourier amplitude ratio of the two horizontal Fourier spectra and one vertical Fourier spectrum were obtained using Equation:

$$r(f) = \frac{\sqrt{F_{NS}(T) \times F_{EW}(T)}}{F_z} \qquad (1)$$

Where r(f) is the horizontal to vertical (H/V) spectrum ratio, F_{NS}, F_{EW} and F_Z are the Fourier amplitude spectra in the NS, EW and Vertical directions, respectively. After obtaining the H/V spectra for the selected segments of the signal, the average of the spectra were obtained as the H/V spectrum for a particular site. The same procedure was repeated at all locations. The peak of the H/V spectrum plot shows the predominant frequency of the site (f_0) and the amplification factor (A_0). Additionally, calculation of standard deviation for each point was done.

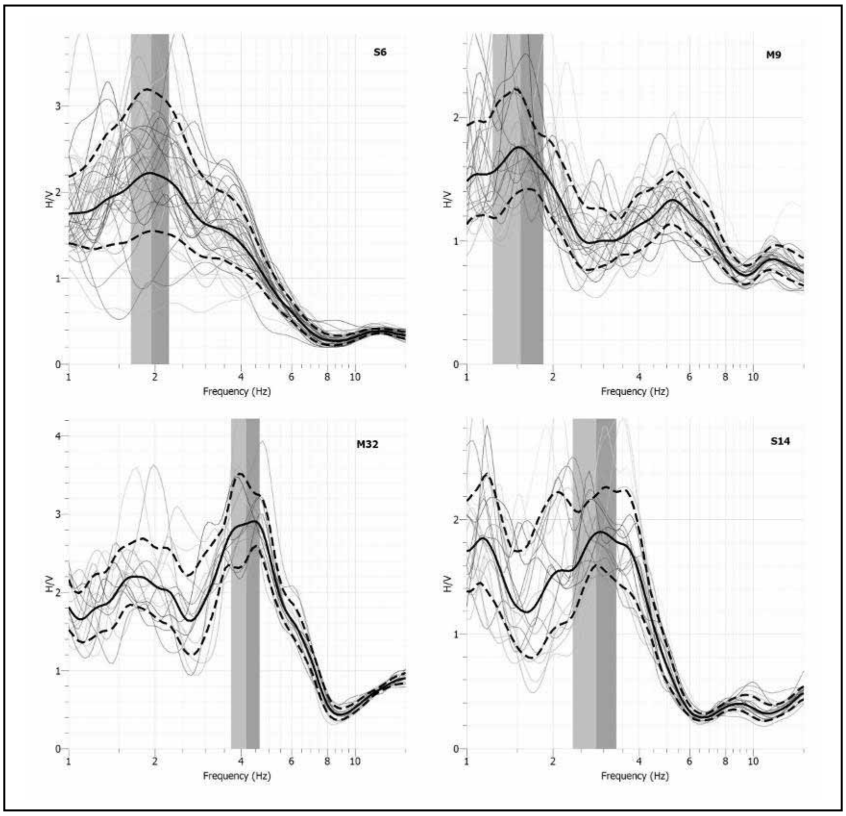

Figure 2. Fundamental Frequency & H/V ratio analyzed at 4 locations in Lefkada town. Thin lines are H/V curves for each selected window. Thick black line is the average H/V curve. Dashed black lines indicate standard deviation of the H/V curve. Grey vertical bars show the selected H/V peak. The width of the vertical bars denotes the range of the peak frequency.

Large standard deviation values often mean that ambient vibrations are strongly non-stationary and undergo some kind of perturbations, which may significantly affect the physical meaning of the H/V peak. In order to assess the reliability and stability of the H/V curves, we examined for each location the individual averaged 3 component spectra for the selected signal windows. In case that the H/V peak lied near or coincide with the spectra peaks (non stationary signal) we reduced the anti-triggering parameter STA/LTA until both sufficient number of windows were present in the calculations and the transient signal was efficiently removed. Following this procedure, we succeeded to define clear H/V peaks independent from transient noise and reduced standard deviation of the H/V curve. Furthermore, the spatial density of measurements allowed the direct comparison of H/V peaks between neighbouring points, as an additional criterion of the H/V clarity and reliability. Two measurements that failed to satisfy the set criteria were excluded from the subsequent developed maps for predominant frequency value and amplification. The increased success rate was mainly due to the knowledge and experience of the operators e.g. avoiding measuring near a tree, and setting of equipment etc likely contributed. In Figure 2 typical examples of calculated H/V curves at various locations are displayed.

Ambient noise SSR analysis

The SSR (Standard Spectral Ratio) technique was applied using the Katouna recordings as reference signal. We performed manual analysis using SAC2000 (1995). All the waveform data were corrected for the DC component and trend. The signals were Fourier transformed, using cosine-tapering before transformation. The amplitude spectra for each location and each component (NS, EW, Z) were smoothed by an appropriate moving average and then divided by the corresponding component of amplitude spectra of the reference site, yielding 3-component SSR curves. The average SSR curve at each site was estimated and the fundamental frequency was visually picked. Due to the reference site installation conditions (buried sensor, no human activity), the small amplitude of the denominator yielded very large, unrealistic amplification factors, which consequently were rejected.

Figure 3 displays the comparison between the H/V and SSR peaks, showing large discrepancies for the majority of locations. This led us to apply the same criteria as for the H/V calculations (examining individual spectra, manually selecting windows of stationary signal etc). However, it was not possible to manually isolate a sufficient number of stationary signal windows for SSR calculations, for numerous sites. The procedure was successful for only 33 locations, for which H/V and SSR peaks show a good correlation (Figure 4). Those 33 SSR amplification frequencies (f_0) were finally adopted. The limited success of the SSR method (less than 45%) compared to H/V shows that transient signal of the temporary stations (human activities, external conditions) is crucial. Therefore, the conditions of installations for both temporary and reference stations should be common, which is not easily applicable in urban areas.

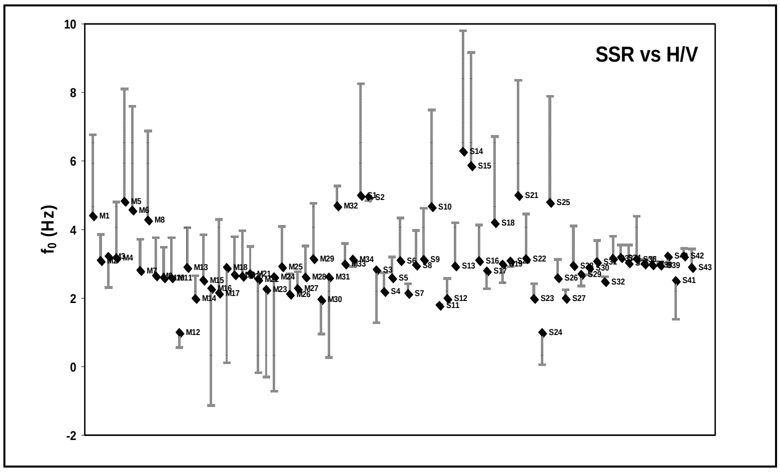

Figure 3. Tomographic slices of the shear velocity model at different depths. Tomograms start at 30 km depth. The velocity perturbations are indicated with a color scale in percent relative to a common reference model, derived from the average shear velocity at each depth.

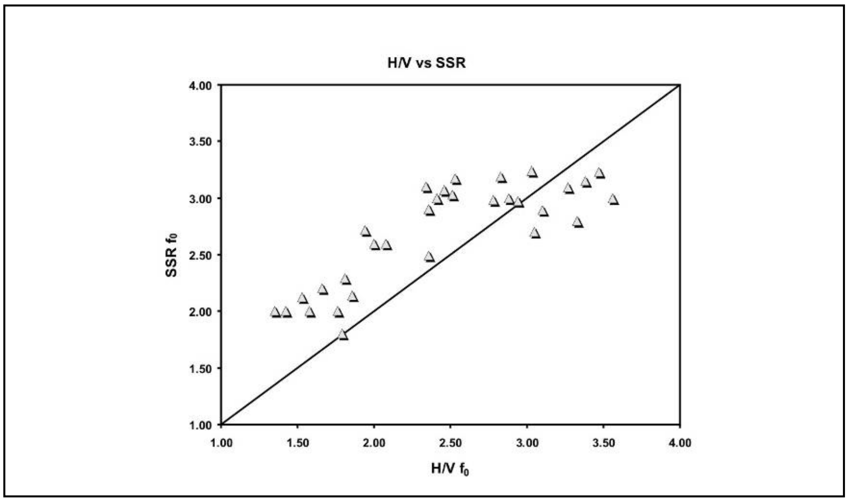

Figure 4. Comparison between H/V and SSR frequency peaks (f_0) for 33 selected locations.

Results and discussion

As previously mentioned, in urban areas, particularly during the day, local noise sources could affect spectral shapes. This effect, however, does not affect the H/V spectral ratios. Thus, the systematic and consistent spectral ratios extracted in this study, likely reflect the physical properties of the local site at the measuring point. On the other hand, the SSR technique was successful for less than 45% of our measurements, yielding however similar peak frequencies to the H/V peaks.

Predominant frequencies (f_0) range between 1-6 Hz. The majority of sites exhibit frequencies between 1.5-3.0 Hz. This distribution of f_0 is in agreement with results obtained by strong motion recordings (experimental and synthetics) at various locations in the town of Lefkada (Gazetas et al., 2004). It is also in agreement with Triantafyllidis et al., (2006) who found predominant frequencies in Lefkada in the range 2-4 Hz, using both seismic and microtremor data. In figure 5 the response spectrum of the 14-8-2003 earthquake recorded at the local Hospital of Lefkada (Benetatos et al., 2007) is shown together with the ambient noise H/V curve recorded at the same location. The predominant PSA frequency of the earthquake is around 2 Hz (0.5 s), similar to the H/V peak frequency, implying that the PGA=0.42g recorded at Lefkada Hospital during the 14-8-2003 strong earthquake was likely the result of resonance phenomena due to the local site response.

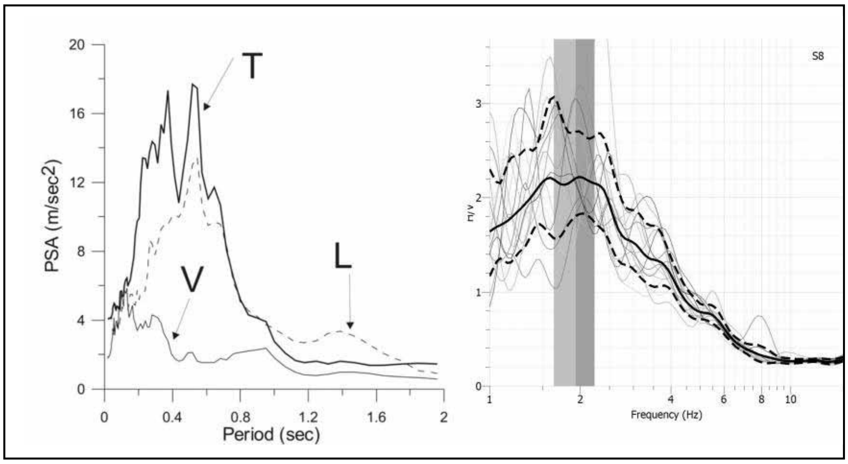

Figure 5. Left: 3-component (L,V,T) Response spectra of the 14-8-2003 Lefkada earthquake recorded at the local hospital (Benetatos et al., 2007). Right: ambient noise H/V curve at the same location.

Amplification factors (A_0) of the H/V curves range between 1.5-3.5. Research experience (SESAME Project) shows that ambient noise H/V peaks show a good correlation with earthquake data concerning the predominant frequencies, however the amplification factors of the H/V amplification factors are decreased by about the order of 2 when compared to earthquakes. Hence, the H/V amplification factors calculated in this study should be considered only as an indicative measure of the expected site amplification in case of earthquake disturbance, but in no case a realistic response parameter. Our results should be evaluated by earthquake recordings from a dense local seismological network installed in the future in the town of Lefkada.

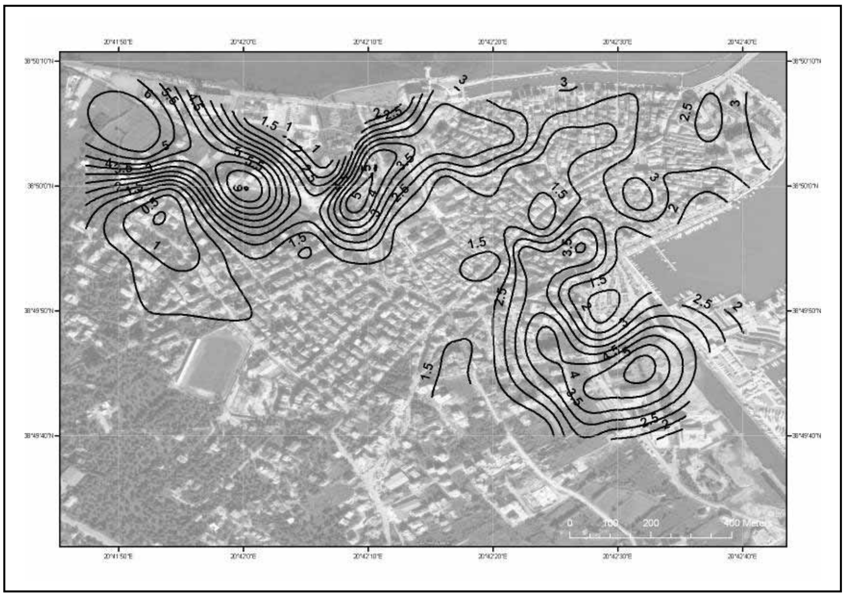

Figure 6. Lateral variations of H/V predominant frequencies (f_0) in the town of Lefkada.

The ambient noise H/V predominant frequencies (f_0) and amplification factors (A_0) were compiled on a ARC-GIS software and corresponding maps of their lateral variations were developed. As we can see in Figure 6, although the geological setting in Lefkada is quasi-uniform, predominant frequency exhibit significant lateral variations throughout the study area.

Higher amplification frequencies are observed along the seaside zone of the town, between 2.4≤f0≤3.1 Hz, in contradiction with the southern promenade where low frequencies are observed (1.7-1.8 Hz). These low frequencies are likely due to the significant thickness (~5 m) of shallow deposits, as data from available boreholes indicate (Papathanassiou et al., 2005). It is highly plausible that extensive ground and wall failures as well as liquefaction phenomena took place in this particular area of the town during the 2003 earthquake, because of interaction of the thick shallow deposits with the strong motion predominant frequency 1.6-3 Hz), which produced severe resonance phenomena.

The area of the north promenade exhibits higher predominant frequencies, ranging between 2.4-3.1 Hz. In that area, damages observed (mainly ground failures) during the 2003 earthquake were of lower magnitude. However, those failures could be possibly associated with resonance phenomena, while the site response frequency lies within the range of the strong motion predominant frequency.

Low frequencies are seen in the central sector of the old town (<2 Hz). The diversification with the area of the north promenade could be associated with the thickness alteration of shallow deposits, which appear thicker by 5 m in the central part of the town (Gazetas et al., 2004).

Low frequencies predominate in the area of the new Lefkada town (western sector), however, the lack of geotechnical information in this area does not allow the direct association with the predominant frequency distribution.

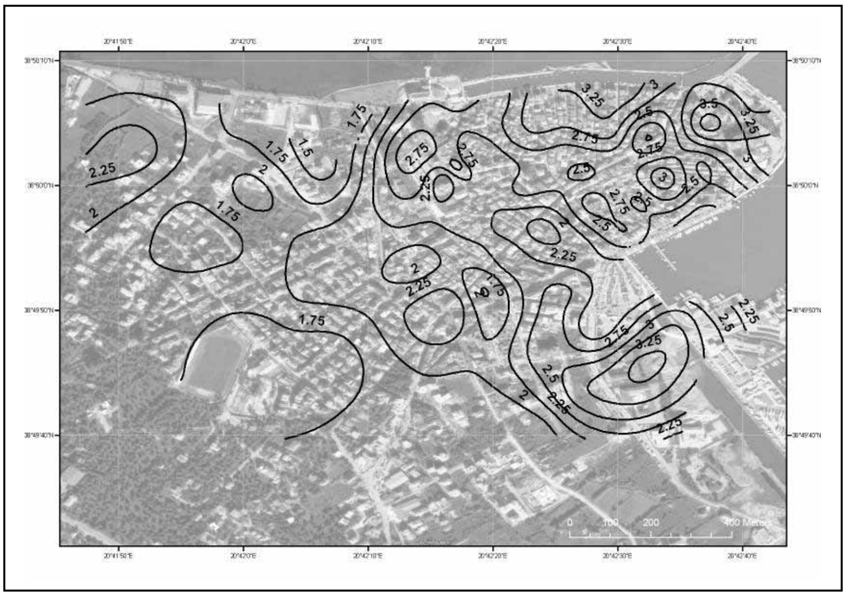

Figure 7. Lateral variations of H/V amplification factor (A_0) in the town of Lefkada.

In Figure 7, lateral variations of the amplification factor (A_0) are displayed. Although results concerning the amplification factor extracted by the H/V ratios are only indicative, it is worth to mention the following:

1. High amplification is observed in the area of the north and the southernmost promenade.
2. Lower amplification in the central sector of the old town.
3. Low amplification in the southern part of the port as well as in the area of the new town.
4.

In general, the region of the old Lefkada town presents higher amplifications with respect to the region towards the west, where the urban area is expanded. Concerning the area of the southern promenade, it is more likely that the observed failures during the 2003 earthquake are due to resonance phenomena rather than seismic energy local amplification due to site amplification.

Conclusions

The large number of ambient noise measurements conducted in Lefkada town allows to draw the following conclusions:

1. Microtremor monitoring is a valuable tool to determine dominant frequency of motion at sites were local site effects are suspected and where microzonation is necessary, particularly in the absence of a large number of strong motion recorders and large number of records over a long period.
2. The methodology adopted and described above proved to be easy, systematic and relatively cheap and the results attained proved to be reliable and repeatable. The H/V peaks appear systematically independent of transient signal peaks, thus can be reasonably associated with the amplification levels at the dominant frequency of the site response functions.
3. The SSR technique was of limited success due to transient noise presence in the temporary measurements. It was not possible to extract realistic amplification factors through

the SSR technique due to the different installation conditions between the temporary measurements in the urban environment and the reference station.
4. Lithology of surface layers must be, as expected, the most important factor controlling the predominant frequency. In general the predominant frequencies appear indicative of the thickness of the sacrificial sediments under the sites.
5. High predominant frequencies (2.4-3.1 Hz) are distributed along the seaside zone of the town, except the area of southern promenade where low frequencies are observed (1.7-1.8 Hz). Low frequencies are met in the central sector of the old town (<2 Hz) and in the area of the new town (<2 Hz).
6. High amplification is seen in the zone of the north promenade, the southernmost port, and at the new town. No amplification is observed at the marl bedrock.
7. The configuration of the sites response frequencies accounts for resonance phenomena during the strong earthquake of 2003 and is possibly the main reason for the extended ground failures and construction damages documented.

Those results are indicative of the site response functions and the 2-D models developed in the study should be considered as preliminary microzonation maps, providing resources to enhance seismic hazard assessment for the town of Lefkada. Our results should however be in the future cross-checked with additional geotechnical information as well as with strong motion responses regarding the local, intermediate and far wavefield.

Aknowlengments

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