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Comparative Study of Microtremor Analysis Methods

DIMITRIOS DIAGOURTAS,[1] ANDREAS TZANIS[1]
and KONSTANTINOS MAKROPOULOS[1]

Abstract— During a multidisciplinary microzonation pilot project in the city of Heraklion (Crete, Greece), microtremor data were collected at the top of exploratory boreholes specifically designed for the purposes of the project, over a period of 5 days, for 4 h/day at 125 Hz (continuous recordings). The data were analysed with the SSR and H/V Ratio techniques, using the standard FFT (applied to long data series) and a Multi-variate Maximum Entropy (MV-MAXENT) spectral analysis method. Both techniques, implemented with both spectral analysis methods, identify the same major resonance frequency band, albeit with different amplification levels. The MV-MAXENT however is effective in handling short data lengths while yielding high resolution spectra and addressing several shortcomings of the conventional FFT (windowing, zero padding etc.). Thus, it yields competitively similar results, with only a fraction (a few minutes) of the data required by the lower resolution (FFT) method and appears to be a powerful tool for site effect investigations. Moreover, the results of both microtremor-based techniques are consistent and remarkably similar to the results of microzonation methods that require (expensive) borehole data.

Key words: Site effect, microzonation, microtremor, ambient noise, maximum entropy spectral analysis.

Introduction

In areas of high seismic hazard, the ever increasing expansion and complexity of contemporary cities and structures has resulted in a corresponding increase of their vulnerability. The imperative requirements for effective seismic risk reduction arising thereof, call for efficient, multidisciplinary and cost-effective microzonation studies. Towards this effect and within the context of a large-scale research program, a team of engineers, geologists and seismologists from several Hellenic universities and private sector companies has carried out a microzonation pilot project entailing the application, comparison and appraisal of existing microzonation analysis methods, while attempting to compile a set of standards and requirements for a complete and effective microzonation study. Part of this project was conducted at the city of Heraklion, (Island of Crete, South Greece), which is affected by the seismic hazard generated in the Hellenic Arc and Trench system.

[1] Department of Geophysics and Geothermy, University of Athens, Panepistimioupolis, 157 84 Athens, Greece. E-mails: diagourtas@geol.uoa.gr; kmacrop@atlas.uoa.gr

A primary task of this project was the comprehension and quantification of the relationship between local geology and ground motion, i.e., the estimation of amplification levels and resonant frequencies across the entire city and their evaluation with respect to local structure. Such a task can be achieved theoretically or empirically, using geotechnical or seismological approaches. The existence of several exploratory boreholes drilled specifically for the purposes of the project, provided an opportunity to test and compare both approaches, focusing especially on the appraisal of the cost-effective seismological methods of Standard Spectral Ratio (SSR) and Horizontal to Vertical Spectral Ratio (HVSR), using microtremor data recorded in their immediate vicinity.

The influence of local geological structure on the spectral characteristics of ambient noise of relatively distant sources has long been recognised. Many authors have studied the nature of the microtremor source, propagation, effects at continental margins and interactions with continental structures (e.g., AKI, 1957; OMOTE *et al.*, 1972; NAKAMURA, 1989; OHMACHI *et al.*, 1991; HOUGH *et al.*, 1992; FIELD and JACOB, 1993; LACHET and BARD, 1994; LERMO and CHAVEZ-GARCIA 1994). Thus, atmospheric disturbances and meteorological phenomena over the land or the sea, as well as distant human activity, have been identified as generators of microtremors propagating as Rg and Lg phases over the continents (a fact that explains their remarkable transmission over long distances). Most of the authors above agree that microtremor spectral characteristics are associated with local geological structure, especially with the density and thickness of the surface layers. In order to quantify this relationship, the most commonly used methods are the well known Standard Spectral Ratio technique which requires the simultaneous measurement of local and remote reference data on bedrock, (e.g., BORCHERDT and GIBBS, 1976; TUCKER and KING, 1984; TUCKER *et al.*, 1984; JARPE *et al.*, 1988; CHAVEZ-GARCIA *et al.*, 1990; BARD, 1995), and the more recent local reference/single-site Horizontal to Vertical Spectral Ratio technique (HVSR), originally applied to microtremors (NAKAMURA, 1989; OHMACHI *et al.*, 1991; FIELD and JACOB, 1993; LACHET and BARD, 1994; LERMO and CHAVEZ-GARCIA, 1994; SEHT and WOHLENBERG, 1999) and later to weak ground motion (AKI, 1993; LERMO and CHAVEZ-GARCIA, 1993; DUVAL, 1994; FIELD and JACOB, 1995; THEODULIDIS *et al.*, 1996) and strong ground motion (LERMO and CHAVEZ-GARCIA, 1993; DUVAL, 1994; FIELD and JACOB, 1995; THEODULIDIS and BARD, 1995; THEODULIDIS *et al.*, 1996; RAPTAKIS *et al.*, 1998). Although most of the studies result in a relatively good representation of the local frequency response, several problems remain under consideration such as, for example, are the effects of 2-D or 3-D structures (with particular reference to basins and alluvial valleys), the nonlinearity of soil response during weak and strong shaking, the attenuation of the wavefield in the subsoil and the realistic prediction of the amplification level of future strong earthquakes. A difficulty particular to the SSR technique is the problem of selecting an appropriate reference site on a healthy outcrop of the bedrock, which at the same time is free of topographic effects; the latter point is crucial for data analysis and interpretation. The HVSR technique is based on the assumption that the local geology does not amplify the vertical component significantly, which is not always true, especially at sites located near (sub)vertical heterogeneities (e.g., faults or lateral lithological discontinuities). Moreover, it is the higher microtremor frequencies that are influenced by nearby ground noise and by scattering in the softer rock layers (e.g., see THEODULIDIS *et al.*, 1996, who concluded that the bedrock H/V amplitude spectral ratio is nearly equal to unity, at least for frequencies less than about 10 Hz).

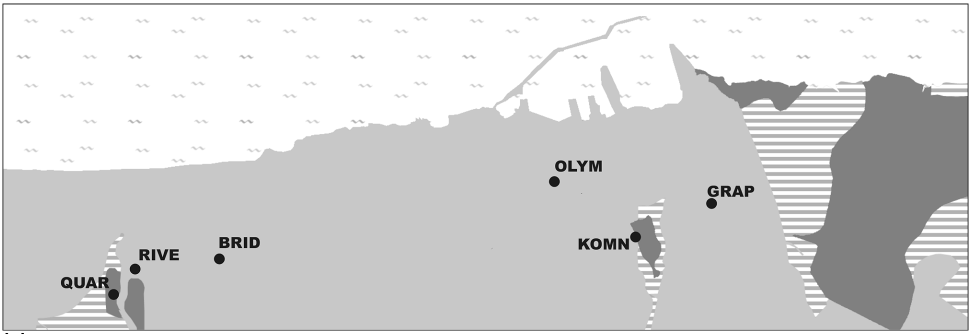
In the present paper, we apply, compare and appraise both the SSR and the HVSR techniques, also exploiting the borehole data which allow adequate understanding of the near surface lithology and stratigraphy. In addition, we introduce the high resolution Multi-Variate Maximum Entropy (MV-MAXENT) spectral estimation method in the analysis of microtremors and site effects, and present its advantages by comparing its results to those of the conventional FFT spectral analysis method.

Data Acquisition and Analysis

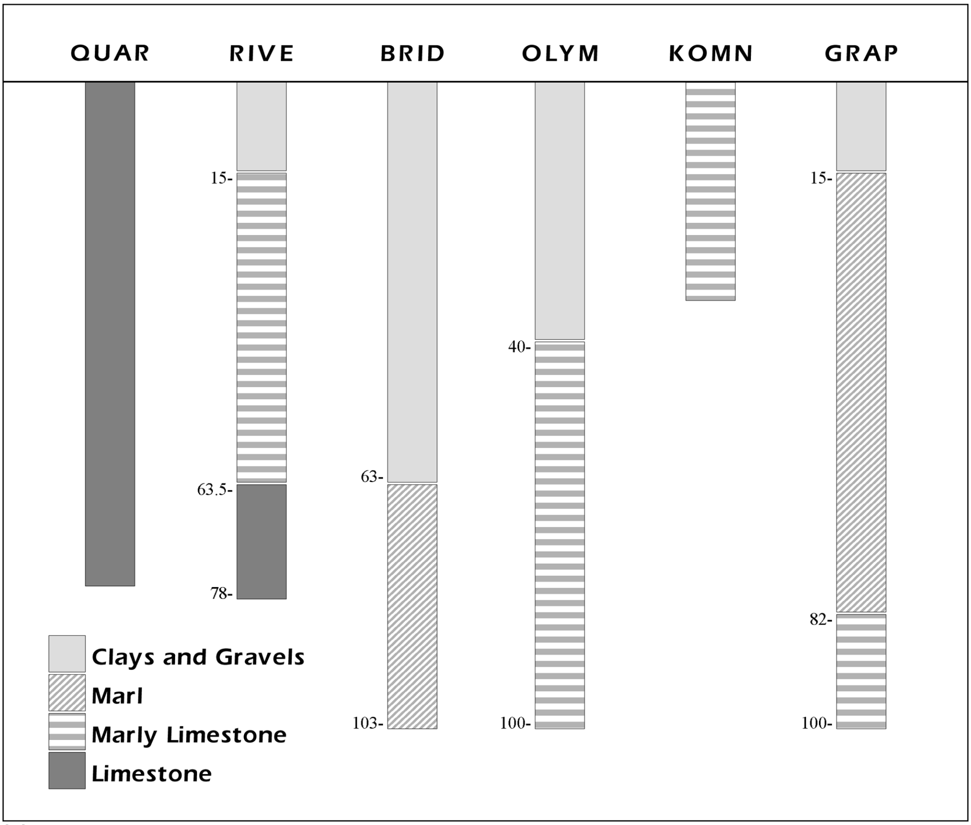
Ambient noise data were collected at the top of four exploratory boreholes with maximum depths of about 100 m, aligned on a line perpendicular to the axis of the 200 m deep alluvial valley on which the city of Heraklion is situated (sites RIVE, BRID, OLYM and GRAP in Fig. 1a). The data set comprised four hours of continuous recordings per day over a period of 5 days, collected at the sampling rate of 0.008 s (125 Hz), using three-component digital seismographs and short-period seismometers with a usable roll-off band of 0.4–1 Hz and a flat frequency response at 1–60 Hz. Two seismographs with the same type of seismometers were installed on the bedrock of either flank of the valley – QUAR on limestone and KOMN on marly limestone (Fig. 1a); these were intended to be used as reference sites for the SSR technique. All instruments were equipped with a DCF receiver. The data were recorded during the time of lowest anthropogenic noise activity (02:00 to 06:00 LT).

Data analysis included the following steps. The continuous data records were divided into 30-minute intervals ($N = 225{,}000$ samples). These were visually winnowed for industrial noise with forbiddingly large amplitudes. The cleaner data subsets were baseline corrected, zero padded and frequency transformed with a standard FFT method. The FFT amplitude spectra were smoothed with a moving average operator, paying attention not to destroy the important spectral peaks. In a final step, the smoothed FFT spectra of the clean 30-minute data subsets were stacked to provide mean spectral values for every component at every site; these were used for the calculation of the spectral ratios.

Before proceeding with the presentation of the results, let us provide a brief note on the effect of noise. The detrimental effects of noise on the SSR technique are obvious. The HVSR technique however requires more attention because in theory,



(a)



(b)

Figure 1a
Geological map of the city of Heraklion (Island of Crete, South Greece), indicating the locations of the seismographs measuring ambient seismic noise.

Figure 1b
Simplified subsurface lithology and stratigraphy compiled from the findings of the exploratory boreholes.

the presence of strong near-field noise amplifies both the horizontal and vertical components identically and cancels out on taking the amplitude spectral ratio. In practice however, it may distort the spectrum by leakage from high power spectral peaks, thus causing underestimation of true H/V ratio. These effects are accentuated when the noise and true ground resonance frequencies coincide.

Finally, we note that in order to facilitate interpretation, the subsurface lithology as revealed by the borehole data was classified into four categories with similar geotechnical characteristics, (clays and gravels, marl, marly limestone and limestone), the stratigraphy of which is shown in Figure 1b.

Results for the SSR Technique

Figure 2 shows the mean spectral ratios at every site, estimated for both the horizontal and the vertical components with reference to the site QUAR (located on limestone). Observe that the same significant spectral amplification is apparent in the high frequency band (> 20 Hz) of all components, at all sites. Figure 3 is the same as per Figure 2, but with reference to site KOMN, located on the softer marly limestone. The mean spectral ratios here do not register high frequency amplification.

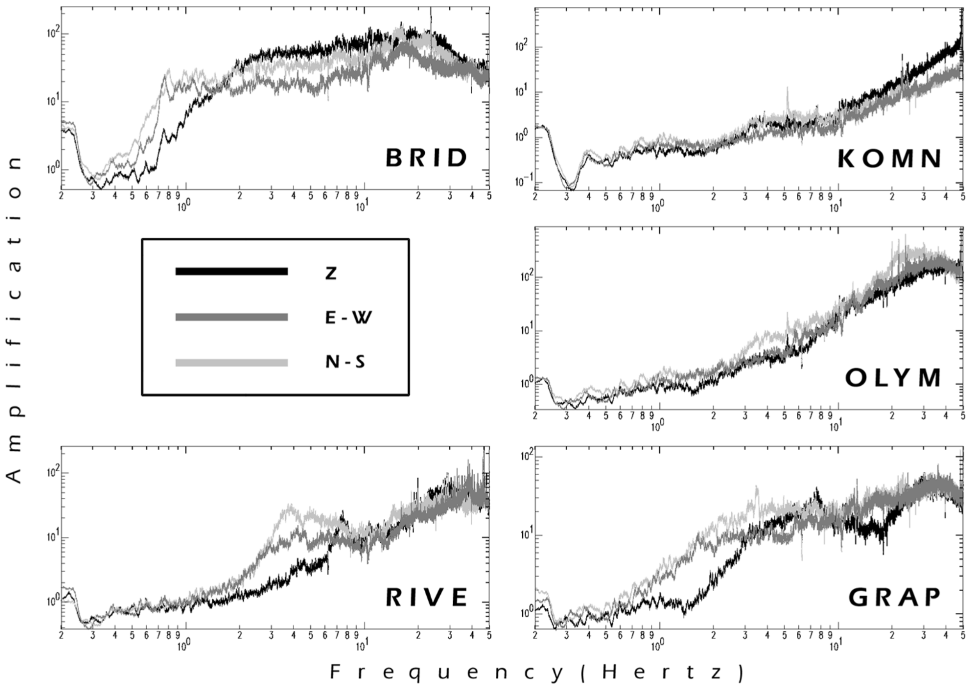


Figure 2
Application of the SSR technique with QUAR used as the reference site.

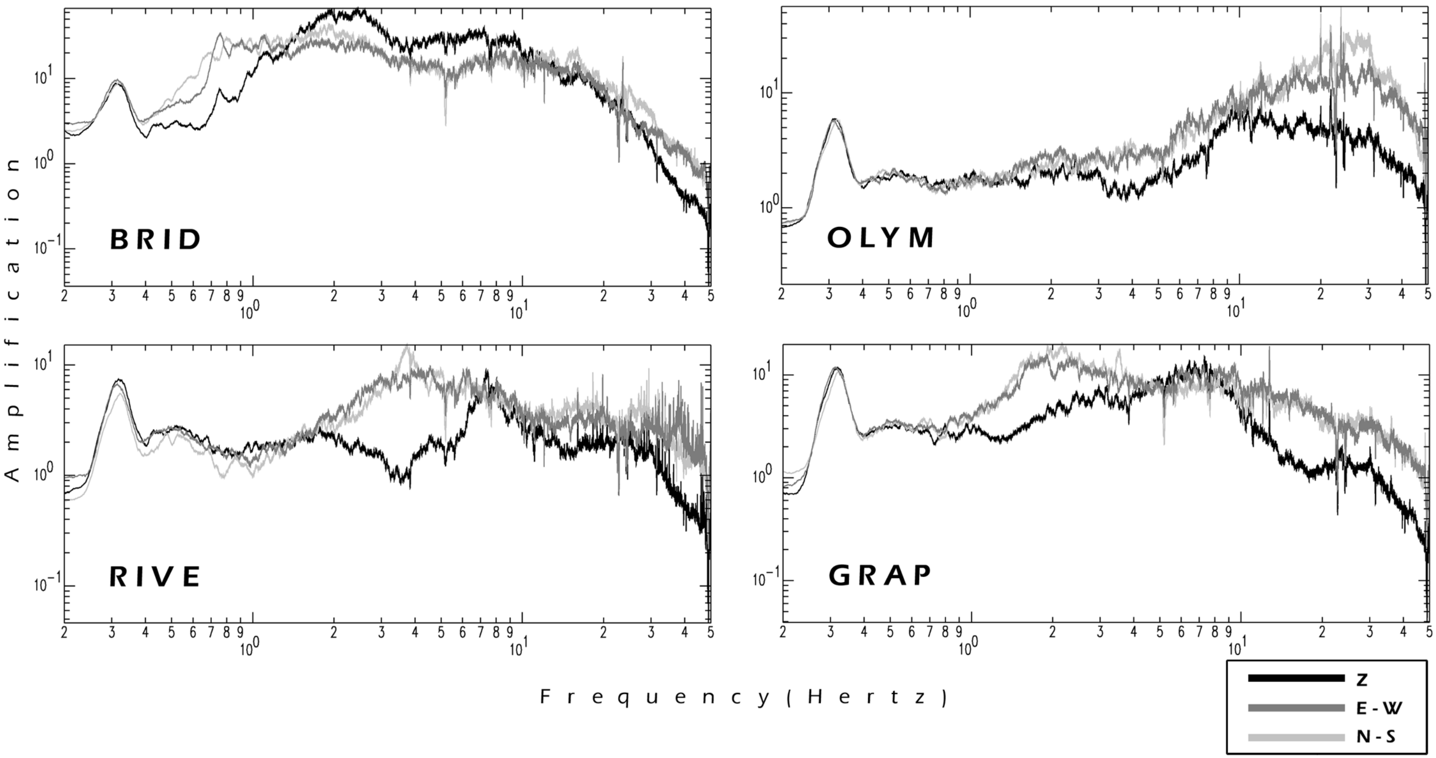


Figure 3
Application of the SSR technique with KOMN used as the reference site.

It follows that the high frequency amplification observed in Figure 2 may be due to wavefield scattering in the softer and less homogeneous marly limestone layer, which invariably exists on top of the limestone bedrock, even if this is not seen in every borehole. The comparison of Figures 2 and 3 further indicates that in some cases there is amplification of the vertical component as well, thus emphasising its importance for interpretation. The amplification of the horizontal components due to resonance in the surface layers is more apparent in Figure 3 (where the reference site is located on the marly limestone); this clearly demonstrates the importance of the reference site properties in data analysis and interpretation. Finally, it can be seen that the amplification at site BRID (located almost at the centre of the Heraklion valley), is observed at the lower frequency band (0.6–1.5 Hz). The data of site GRAP (situated on 82 m of alluvial deposits) are amplified in the somewhat higher frequency band 1.5–2.5 Hz. RIVE and OLYM are located near the flanks of the valley and their data are amplified at very similar frequency bands (2–6 Hz and 3–8 Hz, respectively). It is worth noting that the amplification level is higher at RIVE, which is set above a relatively thinner layer (15 m) of clays and gravel, than at OLYM, which is set above a relatively thick (40 m) layer of the same material.

Results for the HVSR Technique

Figure 4 shows the mean spectral ratios calculated at all sites between both horizontal and the vertical component. It is apparent that the horizontal components at QUAR and KOMN experience no important amplification and the H/V ratio is close to unity, a fact that validates their selection as appropriate reference sites following NAKAMURA's (1989) assumption. The peculiar high frequency ($>$20 Hz) roll-off observed at KOMN is not due to any attenuation of the horizontal components but rather due to the amplification of the vertical component, as has already been observed in Figure 2. At all sites, the resonance frequency bands are similar to the ones observed with SSR analysis, albeit more outstanding. Finally, observe that the amplification levels obtained with the HVSR technique are generally lower than those resulting from the SSR, as has also been observed by other authors (e.g., THEODULIDIS and BARD, 1995; THEODULIDIS *et al.*, 1996; RAPTAKIS *et al.*, 1998). In an attempt to explain this effect, in Figure 5 we plot the mean HVSR and the ratio of the mean horizontal SSR over the mean vertical SSR (for both E-W and N-S components), using QUAR as the reference site. It is apparent that the difference in the amplification level between the SSR and the HVSR is simply the effect of the amplification of the vertical component. The difference between the ratio of the mean Horizontal SSR over the mean Vertical SSR and the mean HVSR depends on the amplification of the vertical component at the reference site, because at the local (measurement) site the first quantity is equal to the product of the second one, by the inverse of HVSR at the reference site. Clearly this is true only in cases where there is no important amplification

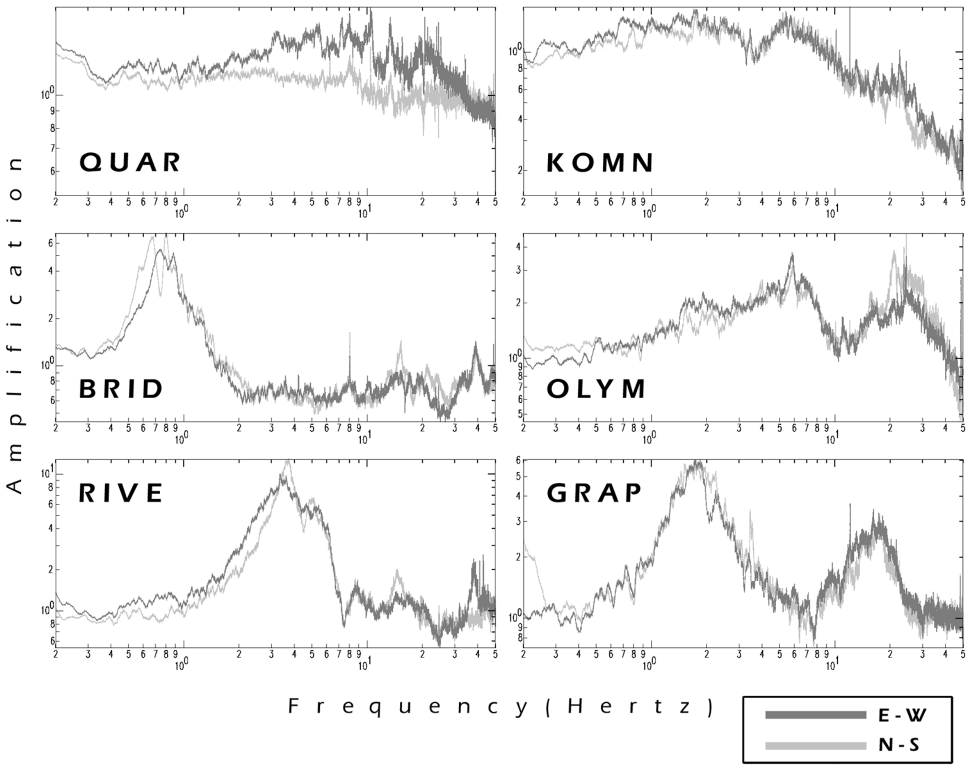


Figure 4
Application of the HVSR technique on both E-W and N-S horizontal components.

of the horizontal components at the reference site, that is if the H/V ratio at the reference site is close to unity throughout the spectrum. This result demonstrates the merit of using the SSR of the vertical component in the interpretation of H/V ratios. It may be argued that the best way to overcome the difficulties inherent in either method, is to apply both of them and jointly interpret their results.

The Multi-variate Maximum Entropy Technique (MV-MAXENT)

The SSR and HVSR techniques make use of spectra computed with the Discrete FT or the FFT spectral analysis techniques. In calculating the power spectrum and associated confidence limits with these methods, it is necessary to smooth over an (often arbitrarily chosen) interval of adjacent power spectral estimates to reduce variance. If the data is assumed to consist of a white noise series $x(t)$ of length $N\Delta t$, the fractional error ε (the ratio of RMS deviation to the mean) in the smoothed spectral estimates is given by $\varepsilon = (2m + 1)^{-1/2}$ when the raw spectral estimates are

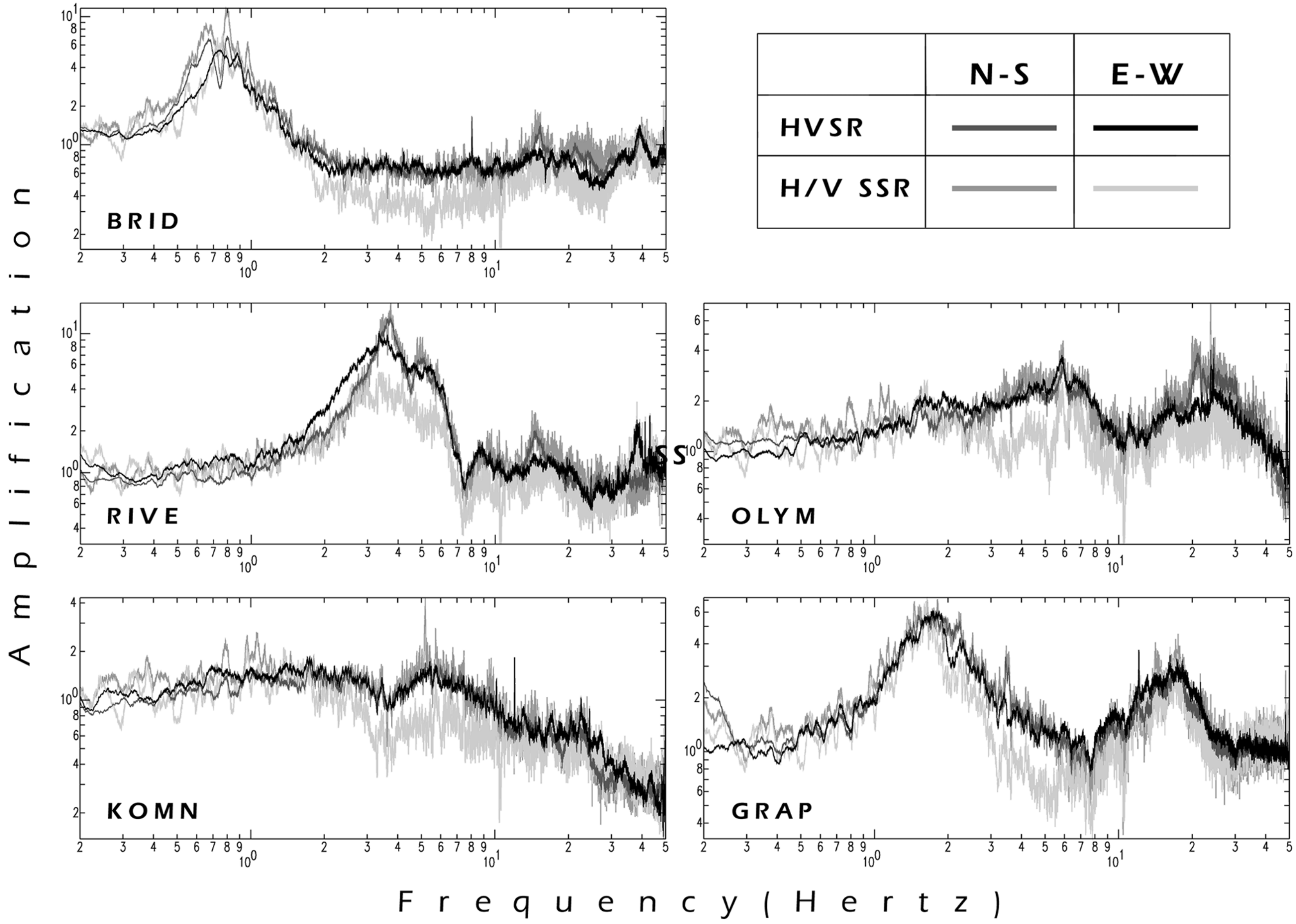


Figure 5
Comparison of the H/V spectral ratios and the ratios between the horizontal/vertical SSR.

averaged over $2m + 1$ points (JENKINS and WATTS, 1968). For a given fractional error, the raw spectral estimates must be smoothed over a frequency interval $\Delta f = (2 \cdot N \cdot \Delta t \cdot \varepsilon^2)^{-1}$. Thus for a stable estimate of the power spectrum, ε must be clearly small and smoothing must extend over a wide frequency range. The reliability of the estimate is improved at the expense of frequency resolution, unless N is made very large. Additional disadvantages of the procedure are that the resulting (smoothed) spectral estimates contain the contributions of several (and often unconforming) frequency-local properties over the interval of smoothing. To obtain highly resolved and statistically robust spectral estimates that display properties localized in frequency, a different spectral approach can be adopted.

It appears that for the case of spectral estimation from a stationary time series, there exists a ubiquitous possibility that we can represent the time series by an autoregressive (AR) process of the form:

$$x(t) = \sum_{m} a(m)x(t-m) + \varepsilon(t)$$

(ULRYCH and BISHOP, 1975; JAYNES, 1982), where $\varepsilon(t)$ is a white-noise error series and $a(m)$ is an absolutely summable filter. Using such a model, it is possible to improve frequency resolution by determining the spectrum from the properties of the filter $a(m)$, $m = 0, \ldots, M$ that best adapts to the given data set. The problem of spectral estimation, then, reduces to that of determining the optimum filter coefficient vector, which can be obtained using a finite portion of the autocorrelation function $R_m = \langle x(t) \cdot (x(t-m)\rangle$ for $m = 0, \ldots, M-1$ where the bracket denotes the ensemble average. BURG (1968) proposed a method for estimating the filter coefficients and hence the power spectrum of a stationary time series in the maximum entropy (ME) sense, that eventually became synonymous with the method.

In order to apply the MAXENT method to the analysis of microtremor data, we need to exercise caution. In general, any straightforward division of spectral estimates independently calculated with the *univariate* (single channel) Burg algorithm will yield unpredictable if not unstable results. The univariate MAXENT (Burg) spectrum is derived under the requirement that it is "*maximally non-committal with respect to the unavailable information*," which is the maximum entropy principle of JAYNES (1963, 1968). As 'unavailable information' the principle defines all the information and probability assignments without the parameter space under consideration (i.e., the time window under analysis). Theoretically, for a second order stationary process where all the expectation values are time invariant, the AR operator derived from any segment of the time series should be able to process any other future or past portion of the same time series. In practice however, most of the measured data are first-order (weakly) stationary, or, only locally stationary. This implies that there are two things that the univariate MAXENT AR operator cannot efficiently do: a) Predictions (information processing) outside the time window for which it has been derived, and b) correlations with other (even simultaneous) time series, especially when they do not belong to the same ensemble (e.g., local and remote microtremor records). This is a consequence of the inherent adaptivity of the technique to the data, and the inevitable differences in the information (signal and noise) content of individual data series. To overcome the above complications, a simultaneous processing of information commonly available in all data channels is needed, i.e., multivariate processing. This can be achieved if we consider a vector time series of the form:

$$\mathbf{X}(t) = [x_1(t)x_2(t)x_3(t)\ldots x_p(t)]^{\mathrm{T}}, \quad t = 1,\ldots,\mathrm{N}$$

consisting of p simultaneous data channels. The equivalent linear AR system will now assume the form:

$$\mathbf{X}(t) = \sum_m \mathbf{a}^{\mathrm{T}}(m)\mathbf{X}(t-m) + \boldsymbol{\varepsilon}(t) \ ,$$

where $\boldsymbol{\varepsilon}(t)$ is a p vector white-noise series and $\mathbf{a}$ is a $p \times p$ vector absolutely summable filter. The power density spectrum will be given by the expression:

$$\mathbf{S}(z) = \Delta t \cdot [\mathbf{A}(z)^{-1}]^{*\mathrm{T}} \cdot \mathbf{P}_m \cdot [\mathbf{A}(z)^{-1}]$$

where $\mathbf{P}$ is the $p \times p$ vector residual error power and $\mathbf{A}(z)$ is the $p \times p$ vector z transform of the filter $\mathbf{a}$. Δt is the data sampling rate and the asterisk denotes complex conjugation. The least-squares minimization of $\boldsymbol{\varepsilon}(t)$ to provide the optimum unit prediction error filter $\mathbf{a}$ has been considered by a number of authors (e.g., STRAND, 1977; MORF *et al.*, 1978) in a more or less direct generalization of Burg's algorithm. The simultaneous treatment of p data channels provides the opportunity for a direct evaluation of both auto- and cross-spectral components using the $p \times p$ operator $\mathbf{a}$.

We conclude this brief presentation of the MV-MAXENT with a note on the statistics of the principal component spectral density estimator. This can be derived from the properties of the generalized linear regression system, whose spectral density matrix is shown to comprise a class of consistent, asymptotically unbiased and asymptotically complex normally distributed estimates (e.g., BRILLINGER, 1981, chapter 8). It is therefore conceivable that the multivariate AR spectral estimator, being a particular case of such a system, will possess similar statistical properties, although the moments of the distribution are yet to the specified. Such an argument is based on and enhanced by the fact that all the entries in the data vector $\mathbf{X}$ are assumed to be second-order stationary time series, jointly normally distributed. This somehow prescribes the result. The number of degrees of freedom associated with the principal components of the spectral density matrix are taken to be $n = \mathrm{N/M}$, as a direct generalization of the result by KROMER (1970) concerning the statistics of the univariate AR spectral estimator. The latter was found to be unbiased, consistent and asymptotically normally distributed. The above arguments provide, at best, an approximation. However, they are based on reasonable assessments and are practical with respect to simple applications such as may be the estimation of confidence limits for the SSR and the HVSSR.

With such properties and statistics of the *multivariate*-MAXENT, we consider and analyze the following vector time series for SSR analysis,

$$\mathbf{X}(t) = [X_j\ X_{\mathrm{BRID}}\ X_{\mathrm{RIVE}}\ X_{\mathrm{OLYM}}\ X_{\mathrm{GRAP}}]^{\mathrm{T}}, \quad j = \text{QUAR or KOMN}$$
$$\mathbf{Y}(t) = [Y_j\ Y_{\mathrm{BRID}}\ Y_{\mathrm{RIVE}}\ Y_{\mathrm{OLYM}}\ Y_{\mathrm{GRAP}}]^{\mathrm{T}},$$
$$\mathbf{Z}(t) = [Z_j\ X_{\mathrm{BRID}}\ Z_{\mathrm{RIVE}}\ Z_{\mathrm{OLYM}}\ Z_{\mathrm{GRAP}}]^{\mathrm{T}}\ ,$$

where X_j, Y_j and Z_j represent the N-S, E-W and vertical components respectively, while any data combination is permissible. Likewise, for HVSR analysis, we consider the vector series

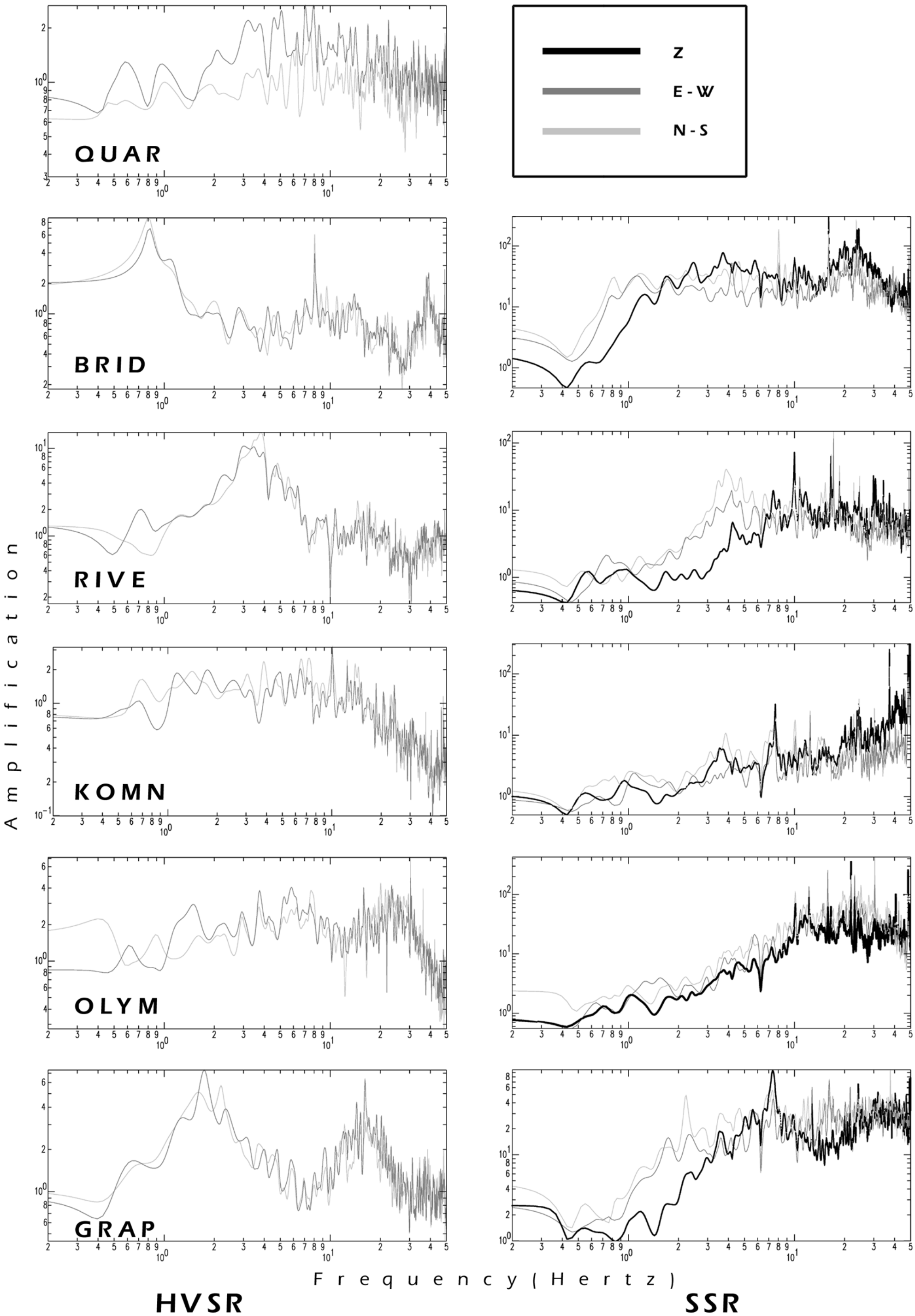
$$\mathbf{D}(t) = [X_j\ Y_j\ Z_j]^{\mathrm{T}}\ ,$$

where the index j refers to any site; any data combination is permissible in this case as well. The spectral analysis algorithm implemented, is a modification of the one due to STRAND (1977). The modifications did not alter the computation of the filter **a**, but rather sought to increase the speed and computational efficiency at the stage of spectral calculations.

One major problem in using the MAXENT method is the determination of the correct order of the AR process, i.e., the number of filter coefficients M that are sufficient to describe the data. If M is too small, the data are underfitted, a smooth spectrum will result and the high resolution capability of the method is lost. Conversely, if M is too large, the data may be overfitted and the spectrum may become unstable. A number of criteria has been developed to establish the correct order of M, such as for instance is the Final Prediction Error criterion (AKAIKE, 1969). It may be shown that in most practical cases (including our data), these criteria fail or seem to be inconclusive. A number of empirical criteria have been suggested for such situations, which limit the order of M to a given fraction of the data length (N) and usually depend on the nature and the statistics of the data. Herein, we follow the same empirical and 'data adaptive' approach. Given that our data were recorded with short-period seismometers, it is appropriate we choose an order M such, that it will fully resolve the lowest useful frequencies available from the response characteristics of the seismometer. Since these are approximately 0.5–0.6 Hz, and given the sampling interval of 0.008 s, we find an M in the range 200–250. As will be shown promptly, this is sufficient to yield useful results.

▶

Figure 6
HVSR (1st column) and SSR (2nd column) techniques implemented with the multivariate Maximum Entropy spectral analysis method, with QUAR used as the reference site.


Z
E - W
N - S
QUAR
BRID
RIVE
KOMN
OLYM
GRAP
Amplification
Frequency (Hertz)
HVSR
SSR

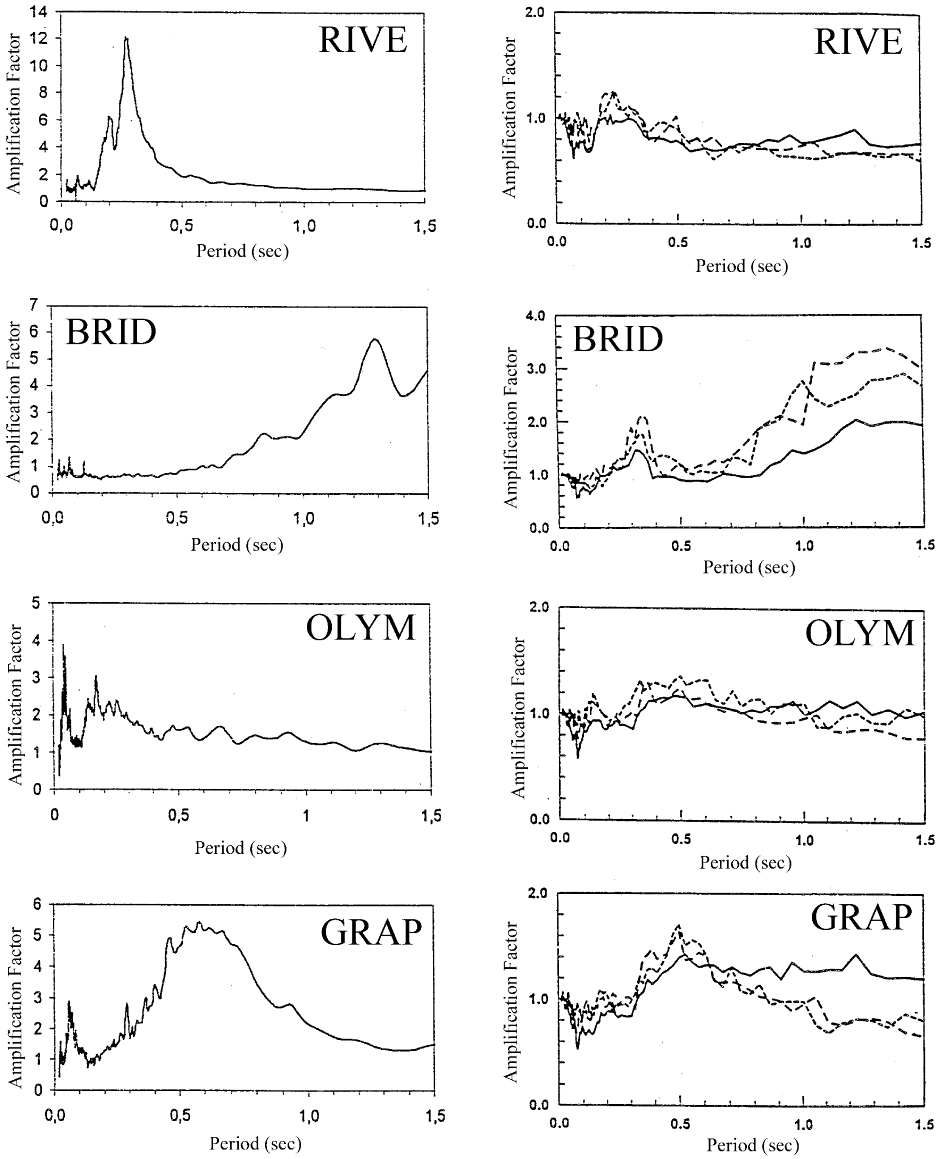


Figure 7
Comparison between seismic (FFT based HVSR) (1st column) and 1-D geotechnical approach for different excitations (2nd column).

In order to demonstrate the performance of the MV-MAXENT, we have calculated the SSR and HVSR power spectral ratios using only 40 seconds of simultaneous data ($N = 5000$) and an AR operator length of $M = 200$. The square root of the power spectral ratios are shown in Figure 6. We can easily observe the same results as per Figures 2–4, which were obtained with mean values of smoothed FFT spectra over 40 data series of 30 minutes duration each ($N = 225000 \times 40$).

Comparison with Geotechnical Data

In order to further validate the microtremor based procedure, Figure 7 presents the comparison between the FFT based HVSR (x axis in seconds) and the 1-D geotechnical approach with three different strong motion excitations (BOUKOVALAS, 1997), at the four sites where geotechnical borehole data were available (EDAFOMIHANIKI, 1996). Remarkable similarity in the amplification frequency bands and important differences in the mean amplification factor can be observed at all sites. The most considerable difference in the mean amplification factor is exhibited at RIVE site located near the valley's western flank. These could be attributed either to the absence of 2-D or 3-D effects within the 1-D geotechnical procedure, or to nonlinear amplification effects between weak and strong seismic motion.

Conclusions

Microtremor data collected during a multidisciplinary microzonation pilot project in the city of Heraklion (Crete), at locations with satisfactory knowledge of subsurface structure, are used for rigorous comparison between site effect investigation methods. The SSR and H/V ratio techniques have been applied, using smoothed Fourier spectra derived from very long time series. Both techniques identify the same major resonance frequency band although with different amplification levels. The main disadvantage of the SSR technique, (selection of the reference site), is addressed by using multiple reference sites, and the importance of the reference site selection is emphasised. The main disadvantage of H/V ratio technique (lower amplification levels) can be explained, at every site, as resulting from local amplification of the vertical component. Multi-Variate Maximum Entropy Spectral Analysis (MV-MAXENT) has been applied and tested with the same microtremor data. MV-MAXENT can handle short data lengths while yielding high resolution spectral estimators and does not have the shortcomings of the conventional FFT algorithm (windowing, zero padding, etc.). Such advantages render the MV-MAXENT a powerful tool, in that it yields competitively similar results with the lower resolution methods, from considerably shorter data lengths. This important property is useful because it will reduce the necessary field-work time of a microzonation survey, thereby increasing cost-effectiveness. Moreover, the results of both microtremor-based techniques are consistent and remarkably similar to the results of geotechnical procedures (at least in the amplification frequency bands).

Acknowledgements

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