H/V Spectral Ratios and Array Techniques Applied to Ambient Noise Recorded in the Colfiorito Basin, Central Italy

by Rosalba Maresca, Danilo Galluzzo, and Edoardo Del Pezzo

Abstract The Colfiorito Basin is a small intramountain depression in the southern section of the Northern Apennine chain that is filled with Quaternary alluvial deposits. The presence of soft alluvial deposits has significantly influenced the level of local damage that was caused by two major earthquakes (\(M_L\) 5.6 and 5.8) belonging to the swarm that started in September 1997. To verify the effects of the basin structure on the predominant frequency of seismic motion, ambient noise measurements were carried out in the Colfiorito Basin during two experiments in May and July of 2002. The horizontal-to-vertical spectral ratios (HVSRS) were calculated for data collected at four profiles in the basin. Array techniques were applied to determine the wave types that composed the noise, to estimate their apparent velocity and azimuth of propagation, and to calculate a velocity-dispersion curve from which a velocity-depth structure was derived. The data analysis shows a high amplification in the HVSR at low frequency. This feature is common to most of the sites, including the reference site, and it is interpreted as being due to weather disturbances. The peak frequencies of the spectral ratio calculated at the sites located in the center of the basin coincide with the theoretically estimated resonance frequencies. The array-averaged HVSR calculated for the array located in the middle of the plain has a pronounced peak at 0.9 Hz. This corresponds to the peak of the amplification function calculated on the basis of the velocity model deduced from the dispersion analysis. The HVSR method is instead unsuitable for the prediction of the resonance frequencies of sediments in the sites where strong lateral variations of basement topography are present. We measured apparent velocities in the range of 0.3–0.8 km/sec by applying \(f-k\) methods to array recordings. These values are compatible with the predominance of surface waves in the noise, as also confirmed by polarization analysis. Both Rayleigh and Love waves are present in the background seismic noise. The results obtained by applying the spatial autocorrelation method to the vertical component of the ground motion recorded at a 240-m-wide circular array deployed in the middle of the basin revealed the presence of Rayleigh waves, and \(f-k\) methods combined with polarization techniques revealed the presence of polarized Love waves. The wave-field analysis indicates two main propagation directions: the first is around N100° E in the frequency band of 1.0–2.0 Hz; this radiation can be interpreted as being generated at the east-southeast step borders of the basin. The second main direction is around N300° E in the frequency band of 2.0–3.0 Hz; its source may be a 180-m-deep depression located at the southwest corner of the basin.

Introduction

The amplification of earthquake motion by shallow sediments is an important parameter in determining seismic hazard. In the presence of a complex subsurface structure, the variation of ground motion can be severe even at very short distances (Riepl et al., 1998); consequently, a detailed map of the site-transfer function becomes necessary, with a dense space sampling of the measurement sites. Techniques that increase the space sampling at affordable costs are ideal for this purpose. Nakamura (1989) showed that the single-station spectral ratio between the horizontal and vertical components is a reliable estimate of the site-transfer function for \(S\) waves, on the hypothesis that the seismic noise mainly consists of Rayleigh waves propagating in a simple geological structure. Because of its easy application, this method
is generally used, although its effectiveness is still under debate, mainly because of the lack of a rigorous theoretical basis (Bard, 1999). In the present study, we have provided experimental constraints that should be useful in this debate, by investigating the wave-field properties of the seismic background noise with small arrays of seismometers that were set up in the same site where a study of the resonance frequencies of the shallow sediments was carried out using the Nakamura technique.

Seismic arrays are a powerful tool for isolation of the coherent wave packets that compose the wave field, allowing estimation of their apparent velocity and propagation azimuth. These, in turn, may be associated to a given source. When combined with polarization techniques, array techniques improve the ability for estimation of the wave composition. Also, array techniques can be used to estimate the surface-wave velocity dispersion curve with direct measures of the apparent velocity as a function of frequency. The velocity structure can be deduced from the inversion of the surface-wave dispersion function (Cornou et al., 2003; Kind et al., 2005). The most used approach for the measurement of the dispersion curve of waves composing background noise is what is known as the spatial autocorrelation (SPAC) method, which was developed by Aki in the 1950s, and which has been recently re-evaluated (see, for example, Chavez-Garcia et al., 2003, and references therein) for its robustness and easiness of application. It is in principle applicable for the assumption of a fully stochastic wave field, composed of wave packets arriving at the array from any direction, but it has recently been shown to be effective even in slightly different situations, where a wave field generated by several sources emitting seismic energy randomly in space and time is superimposed on a wave field generated by one or more deterministic sources (see, for example, Sacco et al., 2003).

In the present study, we have analyzed the ambient noise recorded in the Colfiorito Basin, Central Italy, during two experiments carried out in May and July of 2002.

The plain of Colfiorito is an intramountain basin that is located in the Umbria-Marche region in central Italy (Fig. 1). On 26 September 1997, two earthquakes \( M_L \) 5.6 and 5.8 occurred in this area, causing severe damage in the village of Colfiorito. The distribution of damage was very irregular, with high destruction levels at sites settled on alluvium close to the basin edge that are controlled by faults (Tertulliani, 2000). Previous studies performed in the Colfiorito basin have shown the role of the basin structure in the propagation of seismic waves. Di Giulio et al. (2003) investigated the buried basin structure through prospecting data and analyzed seismograms from moderate local earthquakes recorded by a 2D dense array located in the middle of the plain. They found a predominant frequency of about 1 Hz, which was also confirmed by noise data (Cara et al., 2003), long duration and high amplification of horizontal asynchronous ground motion, and edge-diffracted Love waves that were generated by a 180-m-deep depression at the northwest corner of the basin. Edge-diffracted 1-sec surface waves have also been detected through an analysis of local moderate earthquakes that were recorded by an array located at the eastern edge of the basin (Rovelli et al., 2001).

The present study was aimed at an analysis of the predominant frequency variations in the ambient noise recorded in the Colfiorito Basin through the application of the Nakamura method. The purpose was to correlate the frequency variation with the structure of the basin. We have applied array techniques to data collected at two small aperture arrays set up in the basin to investigate the directional properties of the noise wave field and to recognize the possible influence of the basin structure on the propagation of seismic waves. The presence of surface waves in the noise is derived by the combination of polarization and \( f-k \) analyses. An \( S \)-wave velocity model is calculated by applying the SPAC method to data recorded at a small aperture array located in the middle of the basin. Finally, the calculated velocity structure is used to model the \( S \)-wave site transfer function, as well as the fundamental mode Rayleigh wave ellipticity curve, which when compared with the array-averaged horizontal-to-vertical (H/V) spectral ratio (HVSRS), allows an estimate of the site response in the middle of the basin to be obtained.

Geological Sketch and Experimental Setup

The Colfiorito Basin is a tectonic depression in the southern section of the Northern Apennine chain that is filled with Quaternary alluvial deposits (Fig. 1). A joint approach using geophysical and geological data was adopted by Di Giulio et al. (2003) to measure the spatial variation of the interface between sediments and the high-velocity basement within the Colfiorito basin. Their study showed that the structure of the basin is very irregular, with narrow and deep sags, the deepest of which (up to 180 m and 150 m) are located at the northwest corner of the basin. A relatively flat and shallower (60–70 m) area occupies the center of the basin. Figure 1 shows the depth-to-basement map of the Colfiorito Plain, derived by Di Giulio et al. (2003). The town of Colfiorito is about 400 m to the south of the southwest corner of the map.

We carried out noise measurements in May 2002 along four profiles, investigating 45 different sites that are shown by triangles in Figure 1, and which are characterized by different sediment thicknesses over the basement. A reference site (N2 in Fig. 1) was located on the outcropping rock basement at the southeastern border of the basin, which recorded continuously for the duration of the experiment. In July 2002, a second experiment, which was part of the European SESAME Project (EU EGV1-CT-2000-00026-D06.05. http://sesame-fp5.obs.ujf-grenoble.fr), was carried out in the Colfiorito Basin, with the installation of five arrays. In the present study, we have analyzed part of this data set and, in particular, the data recorded at the two arrays A and B (Fig. 1). The array geometries and performances are de-
Figure 1. Map of the Colfiorito Plain showing recording sites (triangles) and array locations (stars).

scribed subsequently. In both of the experiments, the recording instruments consisted of Lennarz MARSlite stations, which were equipped with LE-3D/5s sensors; the sample rate was 125 samples/sec. All of the stations used Global Positioning System (GPS) receivers for time synchronization. During the July experiment with array configurations, the sensor positions were determined through a differential GPS receiver, to reach adequate positioning accuracy. Instrument response is flat down to 0.2 Hz, with an upper-corner frequency of 40 Hz.

H/V Spectral Ratios

The use of HVSRs of microtremors for site-response estimates was first described by Nogoshi and Igarashi (1970). They showed the relationship between the HVSR and the
ellipticity curve of the Rayleigh waves, which exhibits a sharp peak around the fundamental resonance frequency. Nakamura (1989) showed that the HVSR is a reliable estimate of the site-transfer function for S waves. In discussing the theoretical implications of the Nakamura method, Bard (1999) pointed out that the HVSR is basically related to the ellipticity of the Rayleigh waves composing the noise: the ellipticity exhibits a sharp peak around the fundamental frequency, the amplitude of which depends on the impedance contrast between surface and deep material. This peak is associated with the vanishing of spectral energy of the vertical component, which corresponds to a reversal of the rotation sense of the fundamental Rayleigh wave. In the present study, we have calculated HVSRs of the ambient noise recorded at 45 sites in the Colfiorito Basin and have compared them with the resonance frequencies of sediments. We started our analysis from the noise spectra calculated at the N2 site on hard rock (Fig. 2). We calculated the spectral estimates over seven selected 40-sec long windows collected at intervals of 1 h. The reference-site station operated continuously on 20 May 2002 from 9.00 a.m. to 5.00 p.m. We observed a strong similarity among the spectral shapes recorded at different times, proving the time stationarity of the recorded noise in the interval of recording. A high spectral peak at low frequency, which was more pronounced in the horizontal components, is present in the HVSRs. We calculated the average HVSRs at all of the sediment sites (Fig. 3). Also in this case, high HVSR values were observed at low frequencies, which in some cases appeared as a plateau extending at a frequency higher than 1 Hz (B01, B02, C07, C08, C10, D02, D05). For two sites, A10 and B01, it was possible to compare the HVSRs with those related to the July experiment (Fig. 3, dashed lines). The comparison shows a clear difference at low frequency; the high spectral level observed during the May experiment is absent in the spectral ratio calculated at the nearby site in July. In a previous study of the ambient noise recorded by broadband stations in the middle of the Colfiorito Plain, Cara et al. (2003) observed relative maxima of the spectral amplitude at low frequency, measured on the horizontal components under disturbed weather conditions. This did not significantly affect the shape of the observed 0.9-Hz resonant peak. Cara et al. (2003) compared the long-term variations of low-frequency H/V amplitude with three meteorological parameters observed at a meteorological observatory located about 35 km from Colfiorito and found a good correlation with the wind speed. Duval et al. (2004) evaluated the influence of the weather conditions on the stability and reproducibility of HVSRs on ambient noise. They noted the influence of strong rain on the ambient-noise HVSRs. At the time of the May experiment of the present study, the weather was very disturbed and rainy, even though it was not windy. Taking into account these observations, we interpret the high-amplitude level observed in the spectra of the noise recorded during the May experiment as being due to the disturbed and rainy weather conditions. For each of the sites investigated, we...
Figure 3. Mean HVSRs for the most representative sites in the plain. The data were processed using the HVROCO0_1 code, according to the procedure given in the caption of Figure 2. At the top of each panel, the site code is shown. Dashed lines at the A10 and B1 sites show the average HVSRs of the noise recorded during the second experiment, at one array sensor located within about 20 m of the site. The spectral averages were calculated over twenty-two 40-sec-long time windows, which were selected in the signal through an antitrigger algorithm ($0.01 < \text{sta/fda} < 2.0$). The gray bands mark the fundamental resonance frequencies calculated on the basis of the estimated thicknesses and $S$-wave velocities of the sediments, within 10% uncertainty of the estimated values. The standard deviations are about 30% of the means.
calculated the fundamental resonance frequency of the sediments, according to the formula: \( f_0 = v_S / 4h \), where \( v_S \) and \( h \) are, respectively, the \( S \)-wave velocity and the thickness of sediments. We set the sediment shear-wave velocity equal to 200 m/sec, as estimated by Di Giulio et al. (2003) and confirmed by down-hole \( V_S \) measurements carried out in the middle of the Colfiorito Plain (Rovelli, personal comm., 2003). We estimate the sediment thickness for the sites investigated in the present study from the map of the basement depth shown in Figure 1, interpolated from geophysical and geological data points (Di Giulio et al., 2003). Then we calculated the confidence interval associated with the fundamental resonance frequencies, considering 10% uncertainty on the estimates of shear velocity and thickness. The errors are shown in Figure 3 by the gray band. The comparison of the H/V spectral shapes with the fundamental resonance frequencies showed that sites A06–A14 located in the middle of the basin, where the basement topography is almost flat, show a well-pronounced peak that is coincident with the calculated resonance frequencies. The amplification observed at low frequency does not mask the resonance peak. Other profiles are located in correspondence with narrow inlets of the basin, where the sediment thickness varies sharply over short distances. The HVSRs calculated along these profiles do not show significant peaks associated with the resonance frequencies.

Array Configurations and Performances

The two arrays, A and B, that were installed during the July experiment consisted of 12 stations each. Their geometry was as shown in Figure 4. Array A was located close to the southeastern edge of the basin, whereas array B was in the center of the plain (see Fig. 1). The central stations of arrays A and B were separated by 750 m. The two arrays recorded simultaneously for 3 h on 29 July 2002. We discarded the data from the station of array B that is shown by a square in Figure 4 because of technical problems. The A and B1 configurations were used for the \( f-k \) analyses. The B2 configuration, set up on 30 July 2002, in the same site where the B1 configuration was set up, was used to apply the SPAC method.

To evaluate the array resolution, on the assumption of propagating plane waves, we calculated the Beam-Pattern function (Capon, 1969):

\[
B(S) = \frac{1}{N^2} \sum_{j=1}^{N} e^{j \omega S x_j},
\]

where \( N \) is the number of sensors, \( x \) is their position vector with respect to a reference sensor, \( \omega \) is the angular frequency, and \( S \) is the slowness vector. For a given slowness and frequency, this function only depends on the array geometry and expresses the response of the array to a vertically incident, monochromatic plane wave. The Beam-Pattern function was estimated over a square grid of slowness values ranging from \(-4\) to \(4\) sec/km, with a grid spacing of 0.25 sec/km. This is illustrated in Figure 5 for the three-array geometries and for the central frequencies used in the \( f-k \) analysis, which were set equal to 1.0, 1.5, 2.0 and 3.0 Hz, respectively. The results obtained for the A and B1 configurations show that a main peak is particularly evident at all of the frequencies. Secondary peaks due to spatial aliasing are observed only at 3 Hz, with lower amplitude. The B2 configuration has secondary peaks for frequencies higher than 1.5 Hz. For this reason, we used the B2 configuration only for the SPAC technique.

\( f-k \) Analyses

We used frequency-slowness techniques to investigate the directional properties of the noise wave field in four different frequency bands, where most of the radiated energy was concentrated (Fig. 6). We applied both high-resolution (HR) (Capon, 1969) and beam forming (BF) (Lacoss et al., 1969) methods. Both techniques assume a plane wavefront
Figure 5. Array-response pattern (equation 1 in text) for the array configurations shown in Figure 4 at the four different frequencies indicated at the top of each column.

propagation through the seismic array and are based on an estimate of the cross-spectral matrix $S(\omega)$, the elements of which are given by:

$$S_{jk}(\omega) = \sum_{m=-M}^{M} a_m \cdot d^x_r \cdot \overline{d^x_r} \cdot \frac{2\pi m}{L} \cdot \frac{2\pi m}{L},$$

(2)

where $\omega$ is the angular frequency, $d^x_r (r_j, \omega)$ is the discrete Fourier transform of length $L$ of the signal at the $j$th station in the $r$ position, $a_m$ are the weights used in the smoothing, and $j$ and $k$ are station indices. The BF and HR methods estimate power spectral density according, respectively, to the following relations:

$$\hat{p}^{CV}(k, \omega) = \frac{1}{N^2} U^T(k) \cdot S(\omega) \cdot U(k)$$

(3)

$$\hat{p}^{HR}(k, \omega) = \left[ U^T(k) \cdot S(\omega)^{-1} \cdot U(k) \right]^{-1}.$$ 

In these formulae, $U_j(k) = \exp(ik \cdot r_j)$ are the components of the steering vector $U(k)$ and $N$ is the number of array sensors (Abrahamson and Bolt, 1987). The $f$-$k$ spectra express the amplitude and phase of plane waves propagating in the $x$-$y$ plane with an apparent velocity $c$ and azimuth $\theta$.

$$k_x = \frac{\omega \cos \theta}{c}$$
$$k_y = \frac{\omega \sin \theta}{c}.$$ 

(4)

Before the calculation of the $f$-$k$ spectra, we investigated the spectral properties of the noise recorded by the two arrays to determine the frequencies at which the spectral peaks were most pronounced. We calculated the array-station-averaged spectra for each component of motion, together with the array-averaged HVSRs for the two arrays (Fig. 6). The spectra show significant peaks in the 1- to 3-Hz frequency band, which are more pronounced for the B array. The average spectra calculated at the A array have a higher standard deviation, in particular, at low frequencies, for the horizontal components. We selected the frequency bands where the
Figure 6. Array-averaged spectral estimates obtained for the A and B arrays. The transduction at 70% damping was 400 V·sec/m. For each station of the two arrays, the spectral averages were calculated over twenty selected 16.38-sec-long time windows, for each component of motion. The HVSRs were calculated for each window, merging the horizontal components through a quadratic mean. Finally, the array-averaged spectra were estimated among the averages calculated for each array station. The individual spectra were smoothed using a 1-Hz triangular window.

The most pronounced amplitude peaks of the averaged spectra were observed: 0.8–1.2 Hz, 1.3–1.7 Hz, 1.8–2.2 Hz and 2.8–3.2 Hz. We then selected thirteen 120-sec-long time windows with no spikes and artificial disturbances, by visually inspecting the envelope amplitude of the noise signal. The BF and HR spectra were estimated for the filtered signals (in the previously mentioned bands) on 16.38-sec-long sliding subwindows with 10% overlapping. This led us to calculate more than 800 \( f-k \) spectra for each component of motion recorded at the two arrays, for each frequency band, and for both methods. The search for the power spectral density maxima, corresponding to the best estimate of backazimuth and apparent velocity of the wavefront (equation 4), was performed on a \( kx-ky \) grid ranging in the interval \([-80, 80] \) cycles/km, with steps of 1 cycle/km. Both the BF and HR methods were applied separately on the vertical, north–south, and east–west components of the motion. An example for the A array is shown in Figure 7 for each analyzed frequency band. The dominant spectral peaks obtained with the HR method are sharp and better defined with respect to the results obtained by applying the BF method. The BF spectrum shows more than one specific peak in the frequency band 1.3–1.7 Hz. Despite the differences between the two methods, the location of the maxima practically coincides; therefore, we decided to reject the secondary peaks.

The frequency distribution of the backazimuths that were evaluated with the BF method for the two arrays, for each component of motion and for each frequency band, are shown in Figure 8. The maxima of each Rose diagram are given (in degrees) in Table 1. The apparent velocity does
Figure 7. An example of the frequency-wavenumber normalized spectra obtained over one 16.38-sec-long time window of the east–west component of ground velocity recorded at array A, with the BF (top) and HR (bottom) methods. The frequency bands are given at the top of each column.

not significantly vary for the three components of motion. The values are mostly between 0.3 and 0.8 km/sec. Figure 9 shows the distribution of the apparent velocity evaluated with the BF method for the two arrays, for each frequency band, and for the stacked components.

In summary, the results obtained from the application of the $f$-$k$ analysis to the noise wave field exhibit a background contribution of waves generated by spatially scattered sources, which propagate with low apparent velocity in the 1- to 3-Hz frequency range. Waves with a better-defined direction of propagation are superimposed on the background wave field. One shows a backazimuth of about N100° E in the 1- to 2-Hz frequency band, and a second shows a northwest–southeast direction of propagation that is mostly evident in the 2- to 3-Hz frequency band.

Polarization Properties of the Noise Wave Field at the Array Sites

To better focus on the characteristics of coherent waves revealed by the $f$-$k$ analysis, we studied the polarization of the noise wave field that was recorded by the two arrays using the time-domain algorithm that was proposed by Montalbetti and Kanasewich (1970). The polarization ellipsoid was calculated within sliding time windows by solving the eigenproblem for the covariance matrix. The analyses were extended over the same intervals for which the $f$-$k$ methods were applied. The selected three-component seismograms were first bandpass filtered in the four frequency bands already used for the $f$-$k$ analysis. Then the covariance matrix $S$ in the time domain was calculated. The $S_{ij}$ element is defined by:

$$S_{ij} = \frac{X^T X}{N} = \frac{1}{N} \sum_{k=1}^{N} x_{ik} x_{jk}$$

(k = 1, ..., N; i = 1, ..., 3), (5)

where $X = [x_{ik}]$ is the data matrix in one window, defined as the filtered time series of $N$ samples, recorded at the same station. The indexes $i$ and $j$ take three values corresponding to the east–west, north–south, and vertical components, respectively. The polarization attributes are derived from the orientation of the main axis of the polarization ellipsoid, defined through the azimuth $\phi$, measured clockwise from the north, and the incidence $\theta$, measured with respect to the downward vertical. When the polarization attributes are calculated on the seismic signals for which the direction of wave propagation is known, they help to define the wave types. We performed our analyses for each time window and for each array station, verifying that the results obtained did not significantly vary over the time windows used. Moreover, on the assumption that the polarization properties of the noise wave field do not vary over the short distances sampled by the array sensors, we stacked the results related
to the analyzed time windows, for all of the stations of each array. The Rose diagrams showing the cumulative angular distribution of the azimuth and incidence of the polarization ellipsoid are shown in Figure 10 for the two arrays. The polarization incidence is mostly horizontal in all of the frequency bands. The low values of apparent velocities estimated through the f-k analyses and the predominant horizontal motion suggest the prevalence of surface waves in the recorded signals. The polarization azimuths are quite scattered for array A, whereas at array B, the combined f-k and polarization results show that there is a predominance of coherent radiation propagating in the northwest–southeast direction, with polarization normal to this direction. From this we deduce the existence of Love waves in the noise.

Velocity Structure at Array B and Site-Amplification Function

To analyze the dispersive properties of the noise-wave velocity, we applied the correlation technique defined by Aki (1957) to the vertical ground velocity recorded by array B (Fig. 1). Following this method, the azimuthal average of the correlation coefficients \( \rho(r, \omega) \) calculated for pairs of vertical component records have predictable patterns as a function of the angular frequency \( \omega \) and the station spacing \( r \) as:

\[
\rho(r, \omega) = J_0(\rho_0/c(\omega)),
\]

in which \( J_0 \) represents a Bessel function of zero order and \( c(\omega) \) is the phase-velocity dispersion function. By calculating the azimuthal average of the correlation coefficients at different frequencies and at a fixed distance, it is possible to obtain an experimental correlogram \( \rho(r, \omega) \), from which the dispersion function \( c(\omega) \) can be calculated. We first calculated the spacings between all of the possible station pairs, and then we selected those belonging to the most represented classes of spacing for which the range of azimuths was sufficiently wide (Fig. 11). Eight 4-min-long time windows were selected in the signal, filtered in a narrow-frequency band, in the range 0.5–6.0 Hz with a 0.5-Hz step; for the middle value of each frequency band, the spatial correlation coefficients and their azimuthal averages were calculated for the selected classes of distance (Fig. 12). Then, we derived...
Table 1
The Maxima (in Degrees) of the Rose Diagrams in Figure 8, Showing the Distribution of the Backazimuths Derived by Applying the BF Method to Recordings from the A and B Arrays, for Each Component of Ground Motion and for the Different Frequency Bands

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Array A</th>
<th>Array B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E-W</td>
<td>N-S</td>
</tr>
<tr>
<td>3.0 Hz</td>
<td>280–310</td>
<td>280–310</td>
</tr>
<tr>
<td>2.0 Hz</td>
<td>80–100</td>
<td>280–310</td>
</tr>
<tr>
<td>1.5 Hz</td>
<td>80–100</td>
<td>80–100</td>
</tr>
<tr>
<td>1.0 Hz</td>
<td></td>
<td>80–100</td>
</tr>
</tbody>
</table>

dispersion data (shown as crosses in Fig. 13) by the reading of zero crossings, maxima and minima of the correlation functions. The curves superimposed on the data in Figure 12 were calculated by fitting the experimental correlation coefficients to the Bessel function $J_0$ (equation 6). In this procedure, the argument of the Bessel function is fixed, assuming that the dispersion relationship in equation (6) can be expressed through a simple analytical expression of the form:

$$c(f) = A \cdot f^b,$$

where $f$ is the frequency in hertz and $A$ and $b$ are constants. The best values for $A$ and $b$ (sought over a grid of values varying from 0 to 2, with a grid spacing of 0.02) were estimated by least-squares fitting to the data. The calculated dispersion function is shown in Figure 13. The critical assumption of a simple power-law dispersion function can be validated by the good agreement between the calculated curve, corresponding to the best estimate of the $A$ and $b$ constants, and the individual phase-velocity estimates. To estimate the 1D shear-wave velocity model from the dispersion curve, we used the surface-wave inversion program developed by Herrmann (1987), assuming that this dispersion represents the fundamental mode of Rayleigh waves. We considered as the starting model the one derived by downhole measurements carried out in the middle of the Colfiorito plain (Rovelli, personal comm., 2003), in the same site as array B. Then, proceeding by trial and error, we perturbed the model until we achieved a good fit to the dispersion data. The velocity model producing the theoretical dispersion curve that fits the experimental one best is depicted in the inset of Figure 13, together with the initial model (dashed curve). We observed a good agreement between the theoretical dispersion curve and the experimental phase velocities, despite the low value associated with the half-space in the resolution matrix. To estimate the uncertainty of the estimated velocity structure, we provided a random search of models satisfying the dispersion data, changing layer thickness and shear-wave velocity values in the ranges shown in Table 2.

The inversion procedure was repeated, once for the shear-wave velocity, keeping the values of depth, Poisson ratio, and density in each layer constant, and once for the interface depths, fixing the $S$-wave velocity, Poisson ratio, and density in each layer. The calculated dispersion curves

Table 2
The Thickness and $S$-Wave Velocity Ranges of the Basin Sediments Used for a Random Search of Models in the Inversion Procedure

<table>
<thead>
<tr>
<th>Thickness (m)</th>
<th>$S$-Wave Velocity (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1–7.5</td>
<td>63–77</td>
</tr>
<tr>
<td>47.7–58.3</td>
<td>180–220</td>
</tr>
<tr>
<td>—</td>
<td>800–1450</td>
</tr>
</tbody>
</table>
and the corresponding velocity models are shown in Figure 14, together with their mean values.

The estimated surface-velocity structure can be used to calculate the site-transfer function for vertically incident SH waves at the base of the sediment layers (Idriss and Sun, 1992). In this calculation, the damping coefficient is kept constant in the layers and it is derived from the quality factor estimate furnished for the sediments in other studies (Bindi et al., 2004). We also calculated the HVSRs of the fundamental mode of the Rayleigh waves at the surface for the estimated velocity model using the REIGEN85 routine developed by Herrmann (1987). In Figure 15, the 1D transfer function and the ellipticity at the surface are shown together with the array-averaged HVSR. We see that the frequency of occurrence of the highest peak in the experimental HVSR is approximately 0.9 Hz, in good agreement with the theoretical curves.

Discussion

The seismic site response of the Colfiorito Basin has been studied largely through considering the relevant damage suffered in the basin on the occasion of the two earthquakes (M_L 5.6 and 5.8) that occurred in the area in September 1997 (Tertulliani, 2000; Bindi et al., 2004). Colfiorito is a small intramountain basin with a maximum aperture of about 3 km. Its basement topography is very irregular, with deep and narrow sags crossing the basin. Modeling of 2D and 3D structures is an important tool in the determination of site response, in particular, in relation to basin-edge effects (Kawase, 1996). In small structures like that of Colfiorito, the possibility of multiple reverberations between the borders results in a very complex wave field, which is difficult to analyze. The present study describes how dense array recordings of background noise can help to discern among the seismic phases propagating through the basin. Previous studies have been carried out on earthquakes recorded by small-aperture arrays in the Colfiorito Plain and have shown the genesis of long-duration, basin-induced waves, locally generated from the basin edge (Rovelli et al., 2001; Di Giulio et al., 2003). Basin-edge effects have also been deduced from observation of the damage distribution produced by the two earthquakes that occurred in September 1997, in the area, which was very irregular, with the lowest
intensity on bedrock sites and on the inner part of the basin (Tertulliani, 2000).

We discuss the results obtained in the present study under the next three main topics.

HVS R and Resonance Frequencies

The HVS Rs evaluated in the central part of the basin, where the topography of the substratum is relatively flat, show amplitude peaks that correlate well with the fundamental resonance frequency of the sediments, calculated on the basis of the $S$-wave velocity and the thickness of sediments derived from prospecting data. There is no agreement between the experimental peaks and those predicted theoretically in the sites where strong lateral variations of sediments thickness are present. Our results are in apparent contrast with those of Konno and Ohmaki (1998), who obtained good correspondence between the peak period in the calculated HVS Rs and the fundamental period for sites showing different and complex velocity profiles, spread over a $20 \times 80$-km-wide area. We can explain this apparent contrast by noting that the average dimension of the area investigated by Konno and Ohmaki (1998) was much larger than the Colfiorito basin. The theory that explains the ellipticity of the Rayleigh waves in terms of the resonance frequency is valid for layered systems. Under the good correspondence conditions of Konno and Ohmaki (1998), the multilayered model is still appropriate for each site. In the case of Colfiorito, the lateral variation among the sites is of the same order of magnitude as the wavelength, as opposed to the situation investigated by Konno and Ohmaki (1998), and the assumption of the “layered system” generating a resonance peak in the HVS R is not valid. Other results obtained by Uebayashi (2003) in areas of strong irregular subsurface structures, show as HVS Rs of long-period microtremors do not match the fundamental predominant frequencies of Rayleigh wave ellipticity curves based on 1D stratified models. We do not exclude the possibility that the deep northwest sag in the Colfiorito Basin that is related to the presence of a fault zone can generate a localized amplification of ground motion, focusing seismic energy at depth, as discussed by Di Giulio et al. (2003) and also verified for other basin-like structures (Gao et al., 1996). Moreover, most of the heavy damage produced by the strongest shocks of the Umbria-Marche sequence occurred in sites located on alluvial deposits near to the edge of the basin controlled by faults.
Nevertheless, our experimental results show that in these cases of strong irregularity of the basement topography that is spread over short distances, the Nakamura method is not suitable for the prediction of resonance effects.

In general, evaluated noise spectra show high amplification in the horizontal components at low frequency, which are clearly evident in the HVSRs. This feature is common to most of the sites, including the reference one. As has been known for a long time in Japan and was pointed out within the SESAME project (Deliverable D23.12), sources of ambient vibrations are usually separated into two main categories, natural and human, which very often correspond to different frequency bands. Some low-frequency waves ($f \ll 1$ Hz) are associated with atmospheric forcing, even if this frequency range has very little interest for engineering seismology. For two of the sites investigated in this study, it was possible to compare noise measurements carried out under both calm and disturbed weather conditions: the results show that the amplification at low frequency is present only in the case of disturbed and rainy weather. On the basis of this observation, and taking into account the results obtained in other studies of the influence of weather disturbance on ambient noise (Cara et al., 2003; Duval et al., 2004), the origin of the ambient noise at low frequency measured during the May experiment was put down to atmospheric forcing. However, the amplification in the HSVR observed at low frequency does not affect the shape of the resonance peak.

Basin-Induced Propagation of Coherent Propagating Phases

The frequency-wavenumber analysis applied to the noise recorded by the two arrays in the basin, in selected
frequency bands where the maximum amplitudes are observed in the spectra, reveals the presence of two main directions of propagation superimposed on random background noise. The backazimuth around N100°E/H110°E in the 1.0- to 2.0-Hz frequency band suggests that the noise propagating in that frequency band is generated by the nearby east-south-east step border of the basin. Rovelli et al. (2001) analyzed moderate earthquakes recorded by a small-aperture array in the Colfiorito Basin and observed edge-diffracted 1-sec surface waves. They interpreted these waves as being generated by the eastern step outcrop of the basin edge. The N100°E backazimuth derived in the present study can be associated to the same basin structure. The second northwest–southeast predominant direction of propagation is defined by a backazimuth around N300°E/H110°E and a supplementary one, only detected at the B array, in the 2.0- to 3.0-Hz frequency band. The values of the apparent velocities are in the range of 0.3–0.8 km/sec. The results derived from the polarization analysis demonstrate the existence of a predominant horizontal seismic motion. These last two observations confirm the presence of Rayleigh waves in the signals. Moreover, the matching of the results obtained at the same array from the combined \( f-k \) and polarization analyses reveals the existence of orthogonally polarized waves, propagating in the northwest–southeast direction, which are interpreted as Love waves. We believe that the sharp 180-m-deep depression in the bedrock topography at the northwest corner of the basin is the source of these waves. This is in agreement with the results obtained by Di Giulio et al. (2003), who recognized a coherent horizontal wave train, reaching the surface a few seconds after the direct \( S \) waves, in the seismograms of small-magnitude earthquakes recorded by a 200-m-wide array in the Colfiorito Basin. They interpreted these phases as edge-diffracted Love waves generated by the 180-m-deep depression at the northwest corner of the array.

1D \( S \)-Wave Velocity Structure and Site Response

We applied the correlation method to the noise to evaluate the phase velocity of Rayleigh waves in the 0.5- to 6.0-Hz frequency band. The \( S \)-wave site-transfer function and the ellipticity function of the fundamental mode Rayleigh waves, calculated on the basis of the inferred velocity model, are consistent with the fundamental resonance frequency in the experimental HVSR. An interpretation of the results in terms of an amplification factor is difficult, because the variability in the site-transfer function with the damping in the sediments must be taken into account. Moreover, many studies have emphasized the ability of the Nakamura method to predict the resonance frequency, despite its limits in the evaluation of the amplification of ground motion (Drawinski et al., 1996; Bard, 1999). In particular, in the case of a high-impedance contrast between sediments and basement, the ellipticity peak tends to the infinite and the amplitude of the HVSR resonance peak is hardly related to the \( S \)-wave amplification. A comparison of noise-based estimates with spectral ratios calculated from earthquakes could be proposed for future developments to verify the reliability of the amplification estimates.

Conclusions

Analyses of the ambient noise recorded in the Colfiorito Basin are presented in this study. The aim was to verify the influence of the basin structure on the predominant frequency of seismic motion, through the application of HVSR and array techniques.

The HVSR method applied in the present study is effective in predicting the resonance of sediments for sites located in the middle of basin, where the bedrock topography is quite flat. However, in correspondence to the narrow sags, we believe that the strong lateral variations in the velocity structure over short distances make the HVSR method unsuitable to reproduce the resonance peak.

The \( f-k \) analyses in the 2.0- to 3.0-Hz frequency band show that the propagation of the ambient noise in the Col-
fiorito Basin is controlled by the basin structure. The deep sag located in the northwest corner of the basin is believed to be responsible for the generation of the Love waves, traveling in a northwest–southeast direction. Another predominant backazimuth that peaked around N100°E in the 1.0- to 2.0-Hz frequency band is associated to the eastern step outcrop of the basin edge, believed to be a diffractor for the noise propagation in the basin.

The SPAC method was successfully applied to the array data recorded in the middle of the Colfiorito basin in the 0.5- to 6.0-Hz frequency band. This method, as formulated by Aki (1957), assumes that waves are stationary both in time and in space. Two main directions of propagation were detected from the f-k analysis, superimposed on the background noise. Despite the presence of such directivity in the wave field, we believe that the analysis operated with the SPAC technique is statistically valid, as it displays the average characteristics of the wave field. The SPAC method is applied over a wide frequency range, whereas the detected sources act in narrow frequency bands.

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