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Stability and correlation properties of microtremor response

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ABSTRACT: This study analyzed microtremor records from four stations located at the center and vertices of an equilateral triangle with 52-m sides. The stability of the horizontal-to-vertical spectral ratio (HVSR) was estimated for 12 days of continuous records. The results showed no variation in the frequency and amplitude of the peak spectral ratio over time. Although the amplitude patterns varied slightly at each station, the peak frequencies were consistent within the small four-station array. The results suggest that slight variations in subsurface structure beneath the array may have influenced the HVSR amplitudes. The HVSR estimate had little or no dependency of meteorological variations in atmospheric pressure, temperature, wind speed, rainfall, and humidity measured at a meteorological observatory approximately 1.3 km from the array. Spatial autocorrelation (SPAC) analyses indicated that time averaging of continuous micrometer records from a single pair of stations could serve as an alternative to spatial averaging for the entire array. This result implies that, with the SPAC approach, microtremor records from a single pair of stations rather than a larger array can be applied.

Key words: microtremor, horizontal-to-vertical spectral ratio (HVSR), stability, correlation, spatial autocorrelation (SPAC)

1. INTRODUCTION

Site effects modify seismic motion traveling through the uppermost layers of soil and bedrock. Impedance contrasts between the surface soil layer and bedrock can significantly amplify and augment the duration of ground motions. A number of studies have used microtremor records to assess site effects (see Bonnefoy-Claudet et al., 2006, for an extensive review). Microtremor records are relatively easy to obtain, regardless of site conditions, and can also be acquired without earthquake occurrence or the use of active sources. Because of these advantages, microtremor measurements are particularly useful for estimating seismic microzonation in urbanized areas and/or regions with low to moderate seismicity.

A popular method of estimating the resonant frequency of a site has been to calculate the spectral ratios of horizontal components relative to vertical components (HVSR) in microtremor records (Lermo and Chávez-García, 1994; Field et al., 1995; Konno and Ohmachi, 1998). However, although some studies have proposed that the spectral ratio amplitude can serve as an indicator of site amplification relative to bedrock motion, debate remains regarding this conclusion (Lachet et al., 1996; Satoh et al., 2001). The disagreement may stem from our insufficient understanding of the nature of microtremors. It is therefore important to clarify the limitations and applicability of microtremor records for site-effect assessments. Questions to address are how microtremors respond in subsurface structures, what their physical properties are, and how parameters deduced from microtremor analyses relate to site responses during earthquake ground motions. Moreover, in using short-duration microtremor measurements to evaluate site effects, it has been assumed that the results will be time invariant regardless of the environmental conditions, including both anthropogenic and natural noise conditions. To answer these questions and confirm the above assumption, it is important to validate the stability of microtremor response to the underlying subsurface structure.

In this study, we investigated the stability and correlation of microtremor response properties. We analyzed continuous 12-day records from a small temporary array. Meteorological variations and artificial activities were compared with the microtremor response to examine the influence of external conditions. Spatial autocorrelation (SPAC) analyses were also conducted to investigate the characteristics of microtremor response to the underlying subsurface structure. The SPAC investigation focused on comparing the average cross-correlation for individual station pairs with the azimuthal average of cross correlations from array observations.

2. OBSERVATIONS AND DATA

Microtremors were measured on the campus of the Korea Institute of Geoscience and Mineral Resources. The site is filled with Quaternary alluvial deposits underlying ground that was artificially flattened to create the research complex. These soft sediments overlay a basement rock of Mesozoic granite. We established a four-station triangular array with a distance of 30 m between the central station and each of three vertices forming an equilateral triangle with 52-m sides. Microtremors were recorded with Guralp CMG-40T-

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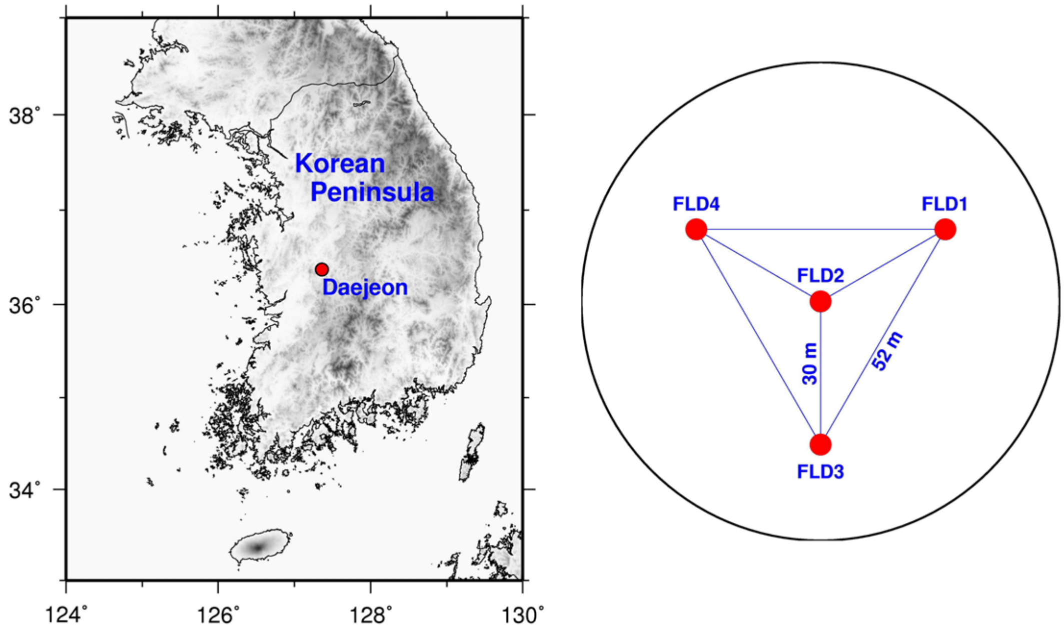


Fig. 1. Location of the field site for microtremor measurements at the Korea Institute of Geoscience and Mineral Resources (KIGAM) in Daejeon (left). Configuration of the array used to record microtremors (right).

Fig. 2. Installation of a seismometer in a free-field site; the seismometer, wrapped in vinyl, was placed in an approximately 30-cm-deep hole and buried with loose soil. Each seismograph was composed of a Quanterra Q330 data logger and Guralp CMG-40T-1 three-component seismometer.

1 three-component seismometers at the natural frequency of 1 Hz and Quanterra Q330 data loggers. Figure 1 shows the site locations and layout of the measurement array. The seismometers were wrapped in vinyl to avoid unwanted direct influences of weather conditions during the experiment (Fig. 2). They were then installed in free-field holes approximately 30 cm deep and buried under loose soil. The seismometers were oriented to geographic north, and each seismograph was synchronized using an independent GPS receiver. Continuous recording was conducted for 12 days at a 200-Hz sampling rate.

3. EFFECTS OF METEOROLOGICAL CONDITIONS

Many studies have reported that meteorological conditions can disturb long-term ambient noise (Longuet-Higgins, 1950; Hasselmann, 1963; Friedrich et al., 1998). Atmospheric disturbances acting on the ground can excite the amplitude variations of microtremors. The main question is whether the influence is equipartitioned between horizontal and vertical components or one component is more amplified than the other. If the former is true, then the atmospheric-induced microtremor fluctuation would be eliminated if we take the HVSR. In this case, both the amplitude and frequency of the HVSR spectral peak would be invariant over the meteorological variations. However, if the latter is true, then caution is required when applying the HVSR to estimate site-effect parameters such as fundamental frequency and the associated amplification factor, although some studies using this method have reported suc-

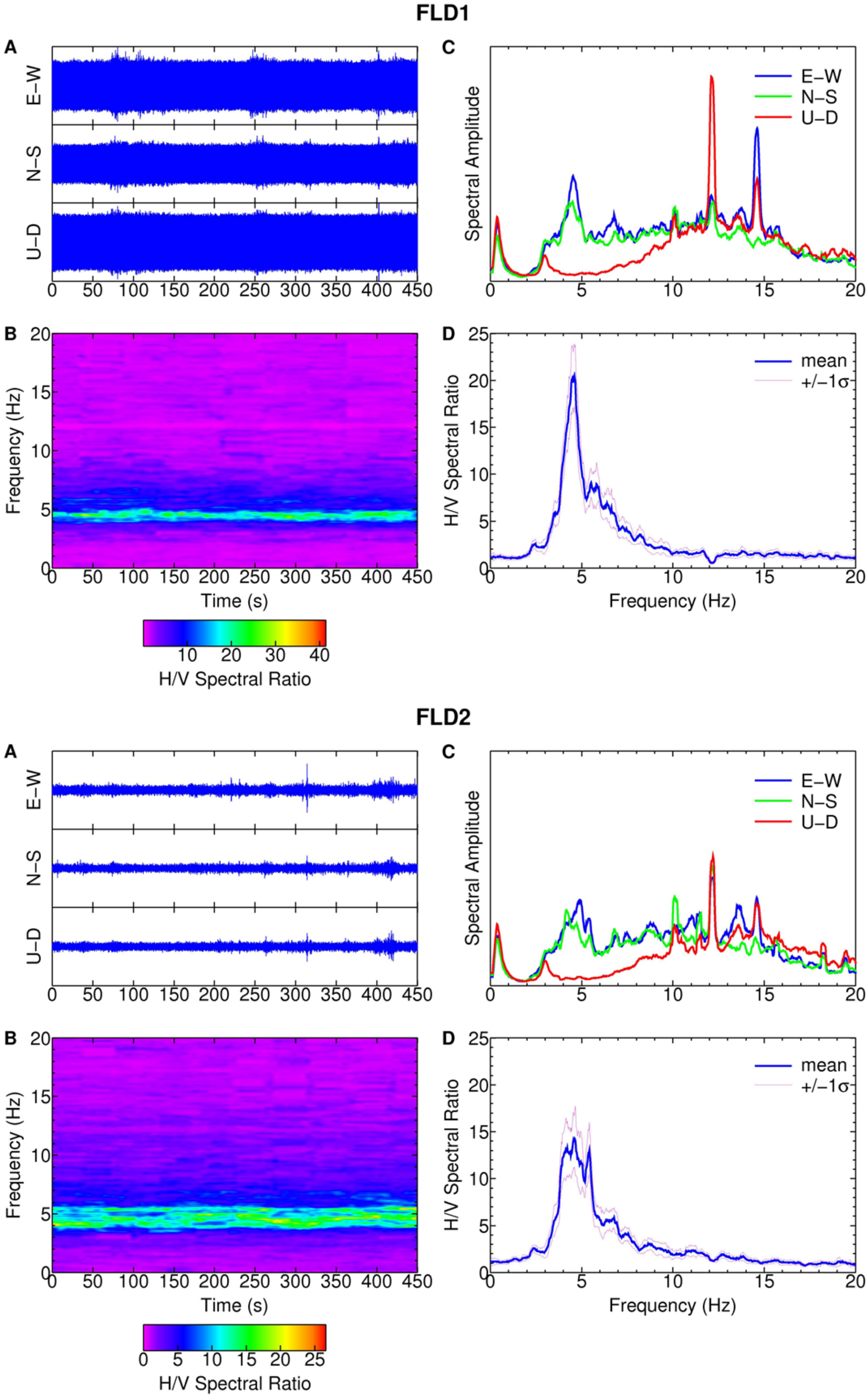
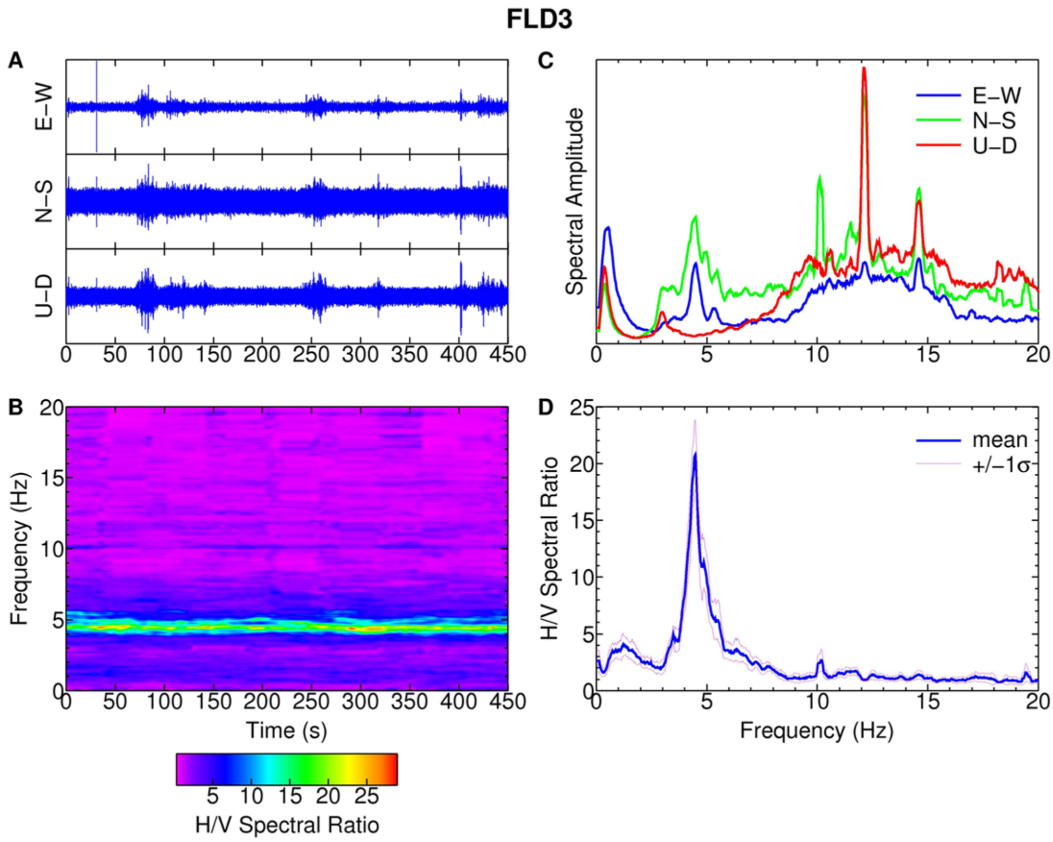


Fig. 3. Stability analyses of the horizontal-to-vertical spectrum ratio (HVSR) for microtremors recorded by the triangular array stations. (A) three-component records of microtremors, (B) temporal variation in HVSR, (C) time-averaged spectral amplitudes of the three components, (D) average spectral ratio with ±1 standard deviations.



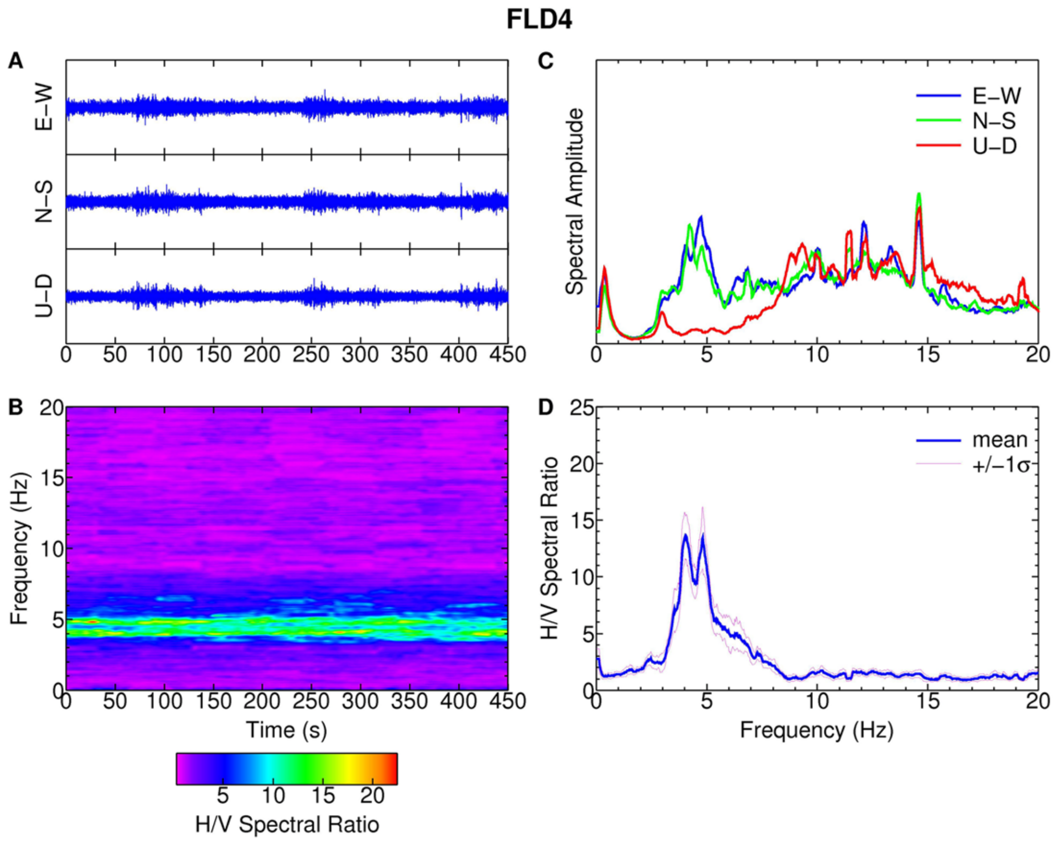


Fig. 3. (continued).

cessful results.

Cara et al. (2003) compared the running amplitude of the HVSR in the 0.1–3-Hz frequency band with the trends in three meteorological parameters (wind speed, atmospheric pressure, and precipitation amount) measured at a meteorological observatory approximately 35 km from their HVSR observation site. They observed that among the meteorological parameters, wind speed had a direct link with the HVSR variations in the low-frequency band below 1 Hz. Mucciarelli et al. (2005) analyzed the influence of wind on seismic noise using observations, experiments, and modeling. They concluded that wind increased the amplitude of the microtremor wave field without affecting the HVSR and suggested that the HVSR variations observed in previous studies might be attributable to direct interaction between wind and the measurement instrument. These conflicting findings regarding the impact of wind on microtremor wave fields imply that the reliability and stability of applying microtremor HVSRs to estimate site effects have not been clearly demonstrated.

We estimated HVSR stability during 12 days of continuous microtremor records (Fig. 3). No variation was found in the frequency and amplitude of the peak spectral ratio over time. Although amplitude patterns varied slightly among stations, the peak frequencies were consistent within the small array. Given that the array measurements were conducted with a single type of seismograph in a flat, open yard, we can assume that the measurement conditions at the surface were nearly equal at all stations in the small-scale array. This suggests that differences in the HVSR amplitude may be related to slight variation in the subsurface structure beneath the array. Unfortunately, we have no direct information on the subsurface structure at the study site and thus cannot provide quantitative analysis of this issue here.

The closest meteorological observatory was located approximately 1.3 km from our study site and was operated by the Korea Meteorological Administration. This distance is much shorter than that in Cara et al.'s (2003) study, and we can expect that the long-period trend in the meteorological observations would reflect that at the microtremor array site. Therefore comparisons between the variation in HVSR and the meteorological parameters in this area might be more informative than those presented previously.

Among the meteorological parameters, wind speed, atmospheric pressure, rainfall, and temperature were compared with the HVSR amplitude for the microtremor array. The meteorological measurements were provided at a rate of one sample per hour except for atmospheric pressure, which was taken at 3-hour intervals. Figure 4 shows the HVSR and meteorological parameters for comparison. The figure shows no noticeable disturbances affecting the HVSR. Even when wind speeds exceeded 5 m/s, there was no clear indication of HVSR variation. This observation implies that HVSR variation depends little on these meteorological parameters.

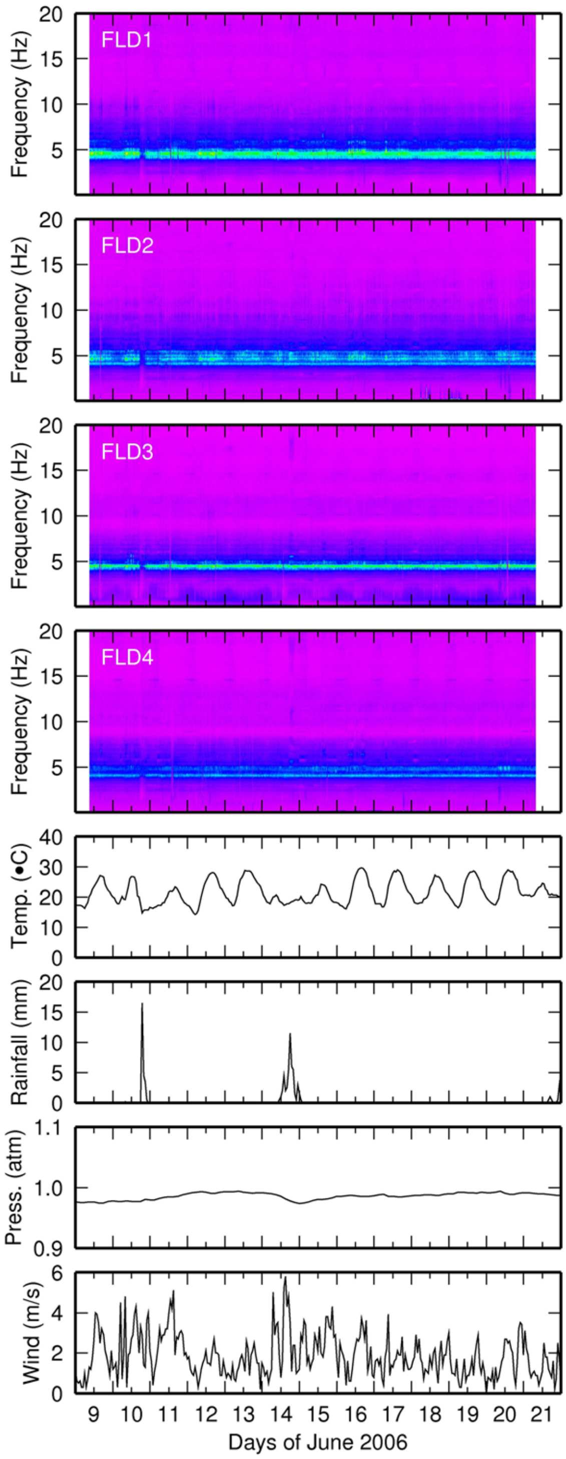


Fig. 4. Comparisons of horizontal-to-vertical spectral ratio (HVSR) with the meteorological parameters.

To investigate the influence of wind on individual components measured by the seismometers, we investigated the amplitude spectra of three-component seismograms. Although the amplitudes of the spectra became large when the wind speed increased, the amplitude variations among the three components were proportional, so stable values were maintained in both the HVSR amplitude and dominant frequency. This implies that the energy induced on the ground surface by meteorological parameters was shared equally among all energy propagation directions in the subsurface.

4. CORRELATION PROPERTIES OF MICROTREMORS

4.1. Role of Surface Waves in Microtremors

Microtremor records were cross-correlated between pairs of components at each seismograph station in the triangular array to investigate which wave types dominated in the microtremor records. Before calculating cross-correlations, the signals were band-pass filtered using a 1- to 10-Hz frequency band to avoid peak amplitude saturation due to any local sources. Figure 5 shows the cross-correlation results between vertical and vertical components (top), vertical and east–west components (middle), and vertical and north–south components (bottom) for station FLD2 at the center of the array. Similar results were found for the other stations (not shown). The correlations show a time delay between the horizontal and vertical motions. The phase shift represented by this time delay suggests that the microtremor records are dominated by ground rolls, i.e., surface waves. However, microtremor records consist of waves propagating in all directions. From such records, the horizontal component cannot be readily decomposed into radial and transverse components, making it difficult to determine

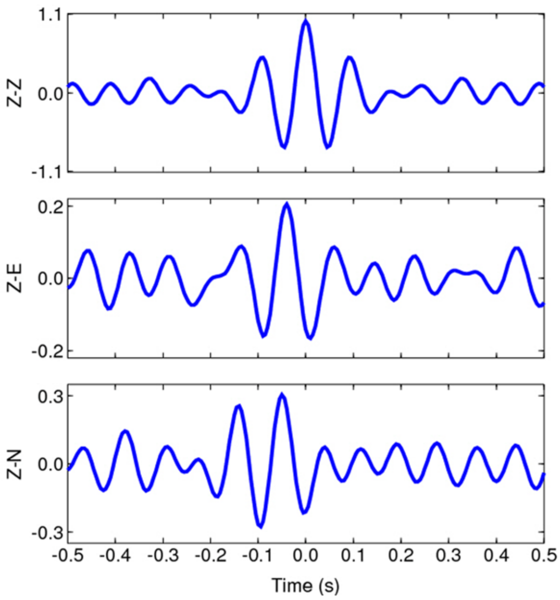


Fig. 5. Cross-correlation results of microtremors between vertical and vertical (top), vertical and east–west (middle), and vertical and north–south components (bottom) of station FLD2. Before calculating correlations, the signal was bandpass filtered using a frequency band of 1.0–10.0 Hz.

whether these correlation functions indicate Rayleigh waves or Love waves.

Several studies have investigated the relative contributions of Rayleigh waves and Love waves in microtremor wave fields (e.g., Chouet et al., 1998; Okada, 2003; Köhler et al., 2007). However, the results show different portions of Rayleigh waves to Love waves, and thus general conclusions cannot be drawn. We interpret this difference as reflecting the site conditions in each study. The sediment type and thickness, impedance ratio of sediment to bedrock, and their geometry within a site may influence the relative development of Rayleigh waves and Love waves in the microtremor wave field.

4.2. Correlation Analysis of Microtremors

If the microtremor wave field is dominated by surface waves, then the dispersion characteristics of the surface waves constituting microtremors may provide useful information on subsurface structures. Aki (1957) proposed that phase velocities of surface waves could be estimated by the azimuthal average of the SPAC function of microtremor measurements. The array technique was also adapted to derive the surface wave dispersion curve from microtremor wave fields recorded by a seismic sensor array (Capon et al., 1967).

Recent applications of temporal cross-correlation of long noise sequences from microtremor wave fields have shown high potential for revealing information on subsurface structures (Shapiro et al., 2005; Sabra et al., 2005; Kang and Shin, 2006). Several studies have reported that SPAC, as a frequency-domain cross-correlation method, has a close relationship with the time-domain cross-correlation method (Chávez-García et al., 2005; Chávez-García and Luzón, 2005; Sánchez-Sesma and Campillo, 2006). These SPAC studies have validated the hypothesis that the average cross correlation of motion between two points over a long time window can substitute for the azimuthal average for all wave directions. This finding implies that the SPAC approach can provide an alternative to the conventional approach based on azimuthal averaging of cross correlations of array observations requiring numerous pieces of observation equipment (e.g., Ferrazzini et al., 1991; De Luca et al., 1997; Cho et al., 2004).

We tested whether the cross-correlation coefficients for a single pair of stations were equivalent to those of the azimuthal average from many station pairs using our microtremor measurements. The average correlation coefficients for each 60-s window were calculated for all three possible station pairs (FLD1–FLD3, FLD1–FLD4, and FLD3–FLD4) having an inter-station distance of 52 m between the vertices in the triangular array. The same calculations were repeated for all three station pairs (FLD1–FLD2, FLD2–FLD3, and FLD2–FLD4) having an inter-station distance of 30 m

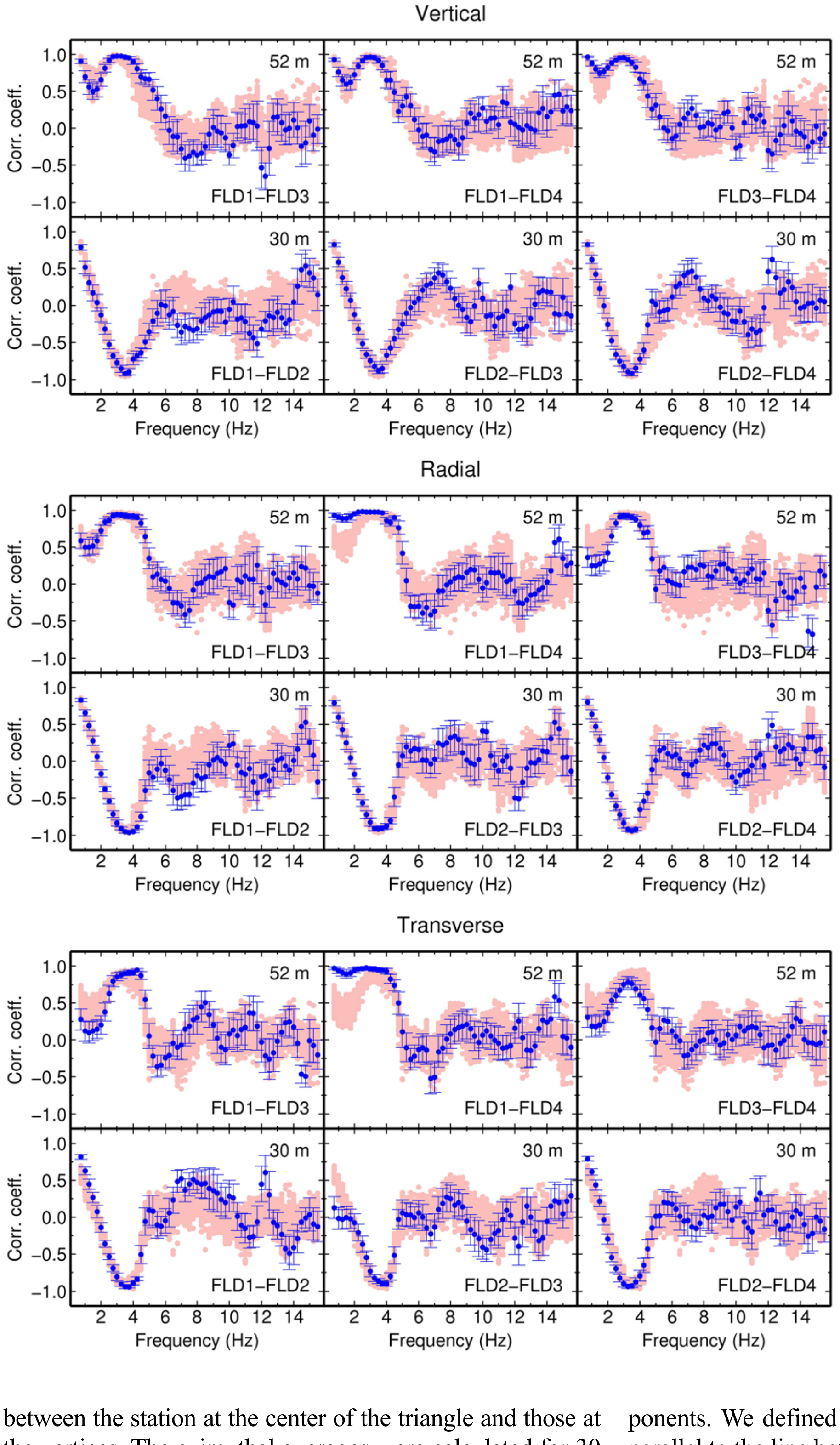


Fig. 6. Comparison of the average cross-correlations between two points over a long time window with the azimuthal average for all the wave directions. The azimuthal averages were calculated for 30 different time windows (dots). The solid circles with error bars in each panel are the average correlation coefficients for a single station pair. Two horizontal components were rotated toward the line linking each pair of stations. Each station pair is indicated in the lower right corner of each panel, and their inter-station distance is shown in the upper right corner.

between the station at the center of the triangle and those at the vertices. The azimuthal averages were calculated for 30 different time windows. Figure 6 shows the results, giving the average correlation coefficients and error bars for each station pair. As the microtremors were recorded in three components, the correlation coefficients were calculated for the vertical component and the two rotated horizontal components. We defined the radial component as the direction parallel to the line between the two stations composing each pair and the transverse component as the direction perpendicular to the line. A slight difference was observed at the low-frequency part of FLD1–FLD4 measurements in the radial and transverse components, and this station pair showed higher correlation coefficients compared to the azimuthal average. This finding suggests that a directional source may exist along the line connecting these two stations. In fact, a road bypasses the study area nearly perpendicular to this line. Traffic along the road might have contributed to the higher correlation at low frequencies in the FLD1-FLD4 records than in the records of other off-perpendicular station pairs. Overall, Figure 6 shows that the azimuthal averages of all three possible station pairs with inter-station distances of 30 m and 52 m are close to the average correlation coefficients for single pairs of stations in each panel. As also noted by Chávez-García et al. (2005), such results verify the hypothesis that the average cross-correlation between two points over a long time window is equivalent to the azimuthal average for all the wave directions.

5. DISCUSSION AND CONCLUSION

For microtremor analysis results to be valid, the parameters at a site should be time invariant, and the use of microtremor records is based on assumptions of the stationarity and isotropy of the microtremor wave field. Microtremors have been applied to determine phase velocity dispersion curves using array techniques such as the frequency-wavenumber (F-K) method and spatial autocorrelation (SPAC) method.

We analyzed microtremor records from a four-station triangular array with a distance of 30 m between the center station and each of three vertices comprising an equilateral triangle with 52-m sides. We estimated the stability of the horizontal-to-vertical spectral ratio (HVSR) during 12 days of continuous records. No variation was found in the frequency and amplitude of the peak spectral ratio over time. Although amplitude patterns varied slightly for each station, the peak frequencies were consistent within the small array. This result indicates that the HVSR amplitude may be related to slight variations in subsurface structure beneath the array.

Our analysis shows that the HVSR estimate had little or no dependency on variation in meteorological parameters, namely atmospheric pressure, temperature, wind speed, rainfall, and humidity measured at a meteorological observatory about 1.3 km from the array. This finding indicates that energy produced on the ground surface by meteorological parameters is shared equally among all the energy propagation directions in the subsurface. Therefore, in microtremor measurements, stable values are maintained in both the amplitude and dominant frequency of the HVSR.

The SPAC calculation showed good correlation between each station pair. Time averaging of microtremor records using continuous data for only one station pair can serve as an alternative to spatial averaging for an entire array. This implies that data from only a pair of stations may be used, instead of observations from a larger array. The microtremor wave field is dominated by surface waves, which have dispersion characteristics. Once correlation coefficients estimated as a function of frequency and distance for each station pair are obtained, these coefficients can be inverted to the phase velocity dispersion curve following the spatial autocorrelation function, represented as a Bessel function of the first kind and zero order as a function of frequency-dependent phase velocity and distance. Thus, microtremor measurements can be used to determine a phase velocity dispersion curve for inversion of subsurface structure and can aid in developing useful models for site-effect estimation.

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