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Site Amplification at Five Locations in San Francisco, California: A Comparison of *S* Waves, Codas, and Microtremors

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Abstract We compare microtremor data to weak-motion *S*-wave and coda recordings at sites in San Francisco in order to clarify the range of applicability of microtremor data to ground-motion prediction. We also compare *S*-wave results to coda results. For each type of data, we compute spectral ratios of motions from two soil/rock station pairs and from an uphole/downhole pair in the Marina district. We compute horizontal/vertical ratios (Nakamura's method) at a soil site, a rock site, and the surface and borehole instruments. In the station-pair analyses, microtremor data show amplifications at the same fundamental frequency as *S* waves, but the frequencies of other peaks do not agree. The amplification at frequencies higher than 2 Hz is greater in the microtremor data. Station-pair ratios of coda data generally show spectral peaks occurring at the same frequencies, but with levels varying from one to four times the amplification from *S*-wave ratios. Nakamura's method of analyzing microtremors agrees better with *S*-wave station-pair results than the microtremor station-pair method over a limited frequency band that varies from station to station.

Introduction

Local site conditions are major factors in the distribution of earthquake damage. Two of the more dramatic and familiar cases in recent history are the Marina district of San Francisco in 1989 (Boatwright *et al.*, 1991) and the lake bed in Mexico City in 1985 (Anderson *et al.*, 1986; Singh *et al.*, 1988). Mainshock and aftershock recordings can be analyzed to identify the frequency content and amounts of soil amplification at the recorder sites. The most commonly used method of analyzing aftershocks, or weak motions, compares a soft-soil site to a nearby hard-rock reference site. Studies employing this method can analyze either the *S* wave or the coda. A recent study indicates that results from the two methods yield different amplitudes (Margheriti *et al.*, 1994).

Unfortunately, we must wait for earthquakes to occur in order to predict amplifications of ground motion using earthquake *S* wave or coda recordings. One of the methods currently used to circumvent this dilemma is the study of microtremors (also known as ambient seismic noise).

Microtremor and aftershock studies generally use similar methods to look for spectral peaks, which are thought to represent resonant frequencies in the response of a site. Some researchers (e.g., Lermo and Chavez-Garcia, 1994) have found that microtremors provide a rough approximation of earthquake site amplification, while others (e.g., Field *et al.*, 1990; Field and Jacob, 1993) consider them less reliable in this capacity. The use of microtremors to study the resonant frequency of sites is a long-standing tradition in Japan (see for example Kanai *et al.*, 1954; Kanai and Tanaka, 1961; Akamatsu, 1984). Microtremors have been used to analyze site conditions in many other regions as well, among them Mexico (Lermo *et al.*, 1988; Kobayishi *et al.*, 1991), Spain (Morales *et al.*, 1991), New York (Field *et al.*, 1990), and the San Francisco Bay area (Akamatsu *et al.*, 1991; Dravinski *et al.*, 1991; Kameda *et al.*, 1991; Seo *et al.*, 1991a, 1991b).

While the use of microtremors for site-response investigation is increasing, studies comparing their results with those from other approaches have produced mixed results. Favorable comparisons of earthquake and microtremor investigations were reported in Japan (Akamatsu, 1984; Kanai and Tanaka, 1961), Mexico (Celebi *et al.*, 1987; Lermo *et al.*, 1988; Lermo and Chavez-Garcia, 1994), and the San Francisco Bay area (Kameda *et al.*, 1991; Seo, 1991a). Some of these studies, however, infer better agreement than the data warrant. Figure 4 in Kameda *et al.* (1991), for example, can be interpreted as showing that microtremor and Loma Prieta mainshock amplifications are independent of each other. Other researchers looking at studies conducted in Mexico (Gutierrez and Singh, 1992), the San Francisco Bay area (Borcherdt, 1970), and El Centro (Udwadia and Trifunac, 1973) have concluded that microtremors do not accurately predict the amplification observed from earthquakes.

Recently, Nakamura (1989) has proposed a single-station method of analyzing microtremors that compares the spectral amplitudes of the horizontal and vertical records (Field and Jacob, 1993; Finn, 1991). Nakamura's method has also been used to analyze aftershock records (Lermo and Chavez-Garcia, 1993).

In this study, we compare site amplifications of microtremors, derived from both the traditional soil-bedrock station-pair spectral ratio method and Nakamura's single-station method, to results derived from Loma Prieta aftershock *S* wave and codas. We find that the site responses (soil/rock spectral ratios) derived from microtremors are consistently higher than those derived from *S* waves and do not always show amplification of the same frequencies, although the fundamental resonant frequency (see Field *et al.,* 1990, for a discussion of this term) is generally the same. Earthquake codas show equal or higher amplifications than earthquake *S* waves, but with similar spectral shapes. The data from a surface and downhole station pair indicate that the increased amplitude of both microtremor and coda site response is due to energy trapped in the basin, a mechanism suggested for earthquake data by Phillips and Aki (1986). Nakamura's single-station method of analyzing microtremors yields results that are in better agreement with the earthquake data than the soil/rock station-pair microtremor method. Applying Nakamura's method to earthquake waves results in spectral ratios that are similar in shape near the fundamental frequency to those from earthquake *S*-wave station pairs, but with higher amplitudes.

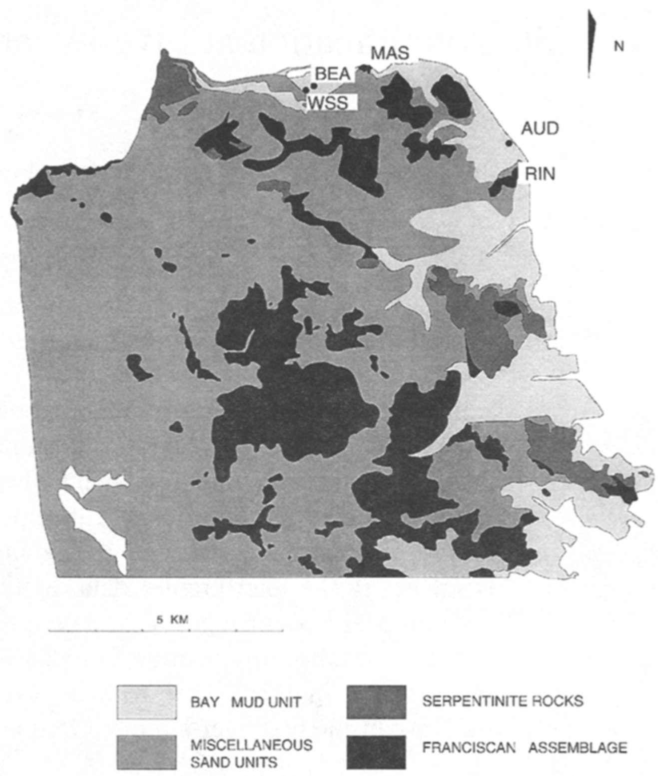

Figure 1. Locations of recording stations used in this study.

Microtremor Recordings

Following the Loma Prieta earthquake of October 18 1989, the USGS deployed a temporary array of 23 GEOS event recorders (Borcherdt *et al.,* 1985) in San Francisco. The deployment is described in Mueller and Glassmoyer (1990). The USGS also installed a permanent downhole-and-surface station at the Winfield Scott School (WSS) in the Marina district of San Francisco (Liu *et al.,* 1992). In the spring of 1993, we recorded microtremors at WSS and at four reoccupied GEOS sites: AUD, BEA, MAS, and RIN. The locations of these five stations are shown in Figure 1. MAS and RIN are bedrock sites. AUD overlies more than 70 m of sediments (Joyner, 1982), including at least 25 m of bay mud (McDonald *et al.,* 1978), near the failed Embarcadero Freeway on the San Francisco Bay waterfront. BEA is in the Marina district near the center of the 1914 hydraulic fill (Bonilla, 1991). The vertical-component microtremor records from station BEA are unusable due to an instrument malfunction, so we were unable to employ Nakamura's method with data collected there. The surface instrument at WSS is on 79.5 m of bay mud (low-velocity clays), sands, and fill. The downhole instrument is in bedrock, at a depth of 88 m. We recorded microtremors simultaneously at these five sites over a period of several days. Recording times are listed in Table 1. WSS and RIN recorded fewer time series than the other stations because of access difficulties and/or instrument malfunctions.

Table 1
Microtremor Recordings

Day	Hour	AUD	BEA	MAS	RIN	WSS
045	00		X	X	X	
045	08		X	X	X	
045	12		X	X	X	
045	20		X	X	X	
046	00		X	X	X	
046	08		X	X	X	
046	12		X	X	X	
046	20		X	X	X	
049	08	X	X	X	X	
049	12	X	X	X	X	X
049	20	X	X	X	X	X
050	00	X	X	X	X	X
050	08		X	X	X	X
050	12	X	X	X	X	
050	20	X	X	X	X	
051	00	X	X	X	X	
054	08	X	X	X	X	
054	10	X	X	X	X	
054	12	X	X	X		
054	20	X	X	X		
055	08	X	X	X		
055	10	X	X	X		
055	12	X	X	X		
055	20	X	X	X		

Time is UTC (subtract 8 hr for local time).

Both aftershocks and microtremors were recorded using L-22 velocity transducers. The microtremor installations at AUD and RIN also used L-4 transducers. The L-4s, with a response to ground velocity that is flat above 1 Hz, have a greater band width and are more sensitive than the L-22s, which have a corner frequency of 2 Hz. Because we found that the spectral ratios from the two transducer sets were almost identical at frequencies greater than 0.4 Hz, we present only data from L-22 transducers.

Earthquake Records

We compared microtremor soil/rock spectral ratios from selected pairs of sites to results from earthquake recordings of both *S* wave and codas at the same pairs of sites. The earthquakes used are listed in Table 2. Most of the earthquakes are from the Loma Prieta aftershock zone, approximately 100 km southeast of the recorders. The instruments were installed and removed at different times, so each station recorded a different subset of the aftershock sequence. Except for WSS, there is some overlap in the earthquake data sets from station to station. The installation at WSS was completed after the removal of the temporary array. Because of the relative proximity of BEA to MAS (1.2 km) and AUD to RIN (0.8 km), we used these pairs to calculate soil-bedrock spectral ratios. There were only three aftershocks recorded by both AUD and RIN, so we also compare AUD to MAS, with a station distance of 3.6 km, and six aftershocks recorded in common. We also calculated soil-bedrock ratios for the uphole/downhole instruments at WSS.

Earthquakes and microtremor data were processed identically. In the analysis of the soil-bedrock station pairs, both of the horizontal components were combined, by taking the square root of the sum of the squared spectral amplitudes, to obtain the vector amplitude. For the single-station method (Nakamura's method), we took the ratio of the combined horizontal components to the vertical. In all cases, prior to taking their ratios, the spectra were smoothed by a Gaussian window of constant width in the log-frequency domain, corresponding to 5% of the center frequency.

The coda segments we analyzed were chosen using Rautian and Khalturin's (1978) observation that the wave propagation processes that give rise to codas stabilize when the elapsed time is two to three times the *S*-wave travel time. Several of the earthquake recordings were too short to give an adequate coda sample. Table 2 indicates which earthquake recordings were used in the coda calculations.

In the interest of consistency, we used a constant time window to calculate spectral ratios for all of the analyses. We chose a 20-sec window length after examining 5-, 10-, and 20-sec windows of *S*-wave accelerograms from earthquakes at BEA and MAS, finding that the longer windows gave better stability and frequency resolution and that they included energy we felt should not be ignored in our site characterizations. To illustrate these points, we show the earthquake records from the event on day 295 in Figure 2.

Table 2
Earthquake Recordings

Event	Mag.	Lat.	Long.	AUD	BEA	MAS	RIN	WSS
2930018	3.9	37.09	121.93		X	X		
2930813	3.6	37.17	122.08		C	C		
2940049	4.3	37.04	121.87		X	X		
2951424	3.7	36.99	121.82		X	X		
2990901	3.6	37.05	121.89		C	C		
3010835	2.5	37.69	122.55	C	C	C		
3021311	2.9	37.06	121.91		X	X		
3040835	3.4	37.05	121.82		C	C		
3060550	4.5	37.07	121.81	C		C	C	
3080716	3.6	37.77	122.16	C		C	C	
3090130	3.7	37.07	121.92	X		X		
3091337	3.8	37.06	121.89	C		C		
3102337	2.9	37.64	122.49	C		C	C	
3112342	4.0	37.23	122.03			C	C	
2300226	3.6	37.29	121.67					C
2371147	3.1	37.87	122.23					C
2661335	3.0	37.38	122.19					C
2780604	3.4	37.07	122.02					C
2820413	2.8	37.28	121.65					X
2870206	3.3	38.05	122.23					C
2920208	2.8	37.98	122.34					C

An "X" under the station name indicates an *S*-wave recording. A "C" indicates both *S* wave and coda. Time is UTC (subtract 8 hr for local time).

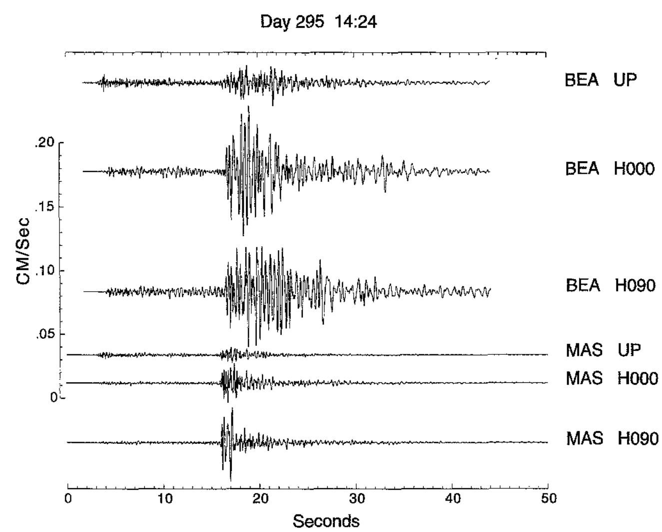

Figure 2. Velocity records at stations BEA and MAS for one of the Loma Prieta aftershocks.

A 5-sec window excludes important large-amplitude arrivals following the direct *S* wave at BEA. The records at MAS (the bedrock reference site) have much simpler *S* arrivals. Comparison of the spectral ratios between BEA and MAS for the eight events co-recorded at these sites (Fig. 3) illustrates the effect of the window lengths in the frequency domain. The peak at 0.9 Hz that is evident in the 10- and 20-sec windows disappears if we use a 5-sec window. This spectral peak is caused by persistent energy (apparently trapped in the Marina Basin) at that frequency, some of which is cut off by

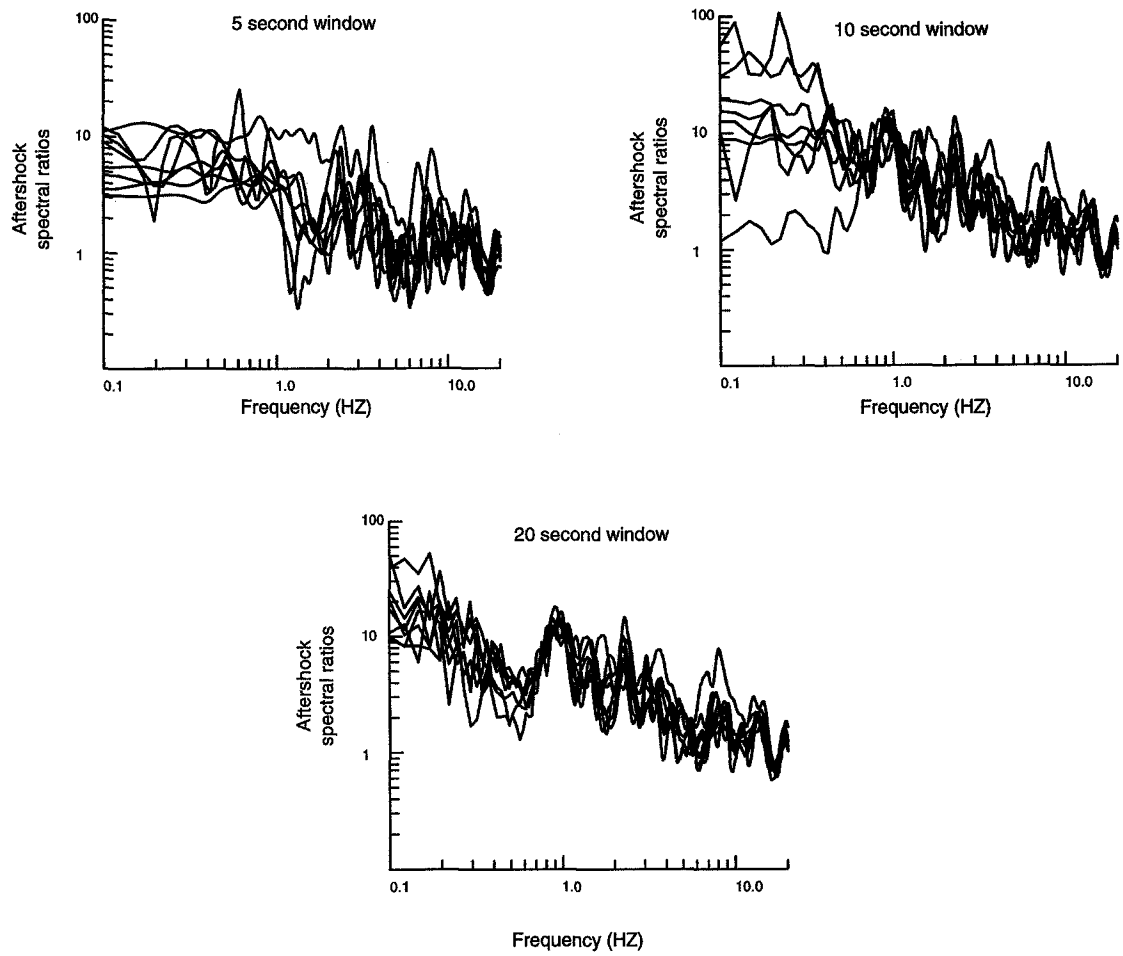

Figure 3. *S*-wave spectral ratios for the BEA/MAS station pair. The window refers to the length of the time sample used to calculate the spectra.

the shorter window length. The scatter in the 10-sec-window data at low frequencies is reduced if we use 20 sec. A few of the records were too short to contain 20 sec of coda. In those cases, we used as long a window as we could. We excluded records from our coda analysis if there was not at least 10 sec of coda. There were 6 of the 14 coda records less than 20 sec, with 3 of those less than 15 sec.

Nakamura's Method

Spectral ratios derived from two nearby stations may show the amplification of one station with respect to the other. If one station is on soil and the other is on rock, we interpret the amplification as due to propagation effects in the soil. It is not obvious why taking the ratio of the horizontal to the vertical components at a single station on soil (Nakamura's method) should give the same result. Nakamura's rationale (Nakamura, 1989; Finn, 1991) claims that the effects of the Rayleigh wave are eliminated by examining the H/V ratio. More recently, it has been suggested (Lermo and Chavez-Garcia, 1994; Lachet and Bard, 1994; Field, written comm.) that, instead, it is the Rayleigh wave that is responsible for the success of Nakamura's method. According to these authors, the peak at the fundamental frequency of a layer is caused by the vertical component of the Rayleigh wave going toward zero.

Results from Station Pairs

Figure 4 shows the aftershock *S*-wave spectral ratios, the coda spectral ratios, and the microtremor ratios for the four station pairs. All of the earthquake ratios show a well-defined peak at about 1.0 Hz. Both the *S*-wave and coda ratios show small deviations at high frequencies, with AUD/MAS showing the most scatter. Liu *et al.* (1992) observed variability in the amplitude of the 1-Hz spectral peak at WSS as a function of earthquake location and ground-motion direction. The observed amplitude variation is small, less than a factor of 2. This is less than, or comparable to, variability at the other sites, with most of their source earthquakes located in the Loma Prieta aftershock zone.

The microtremor soil/rock horizontal spectral ratios are

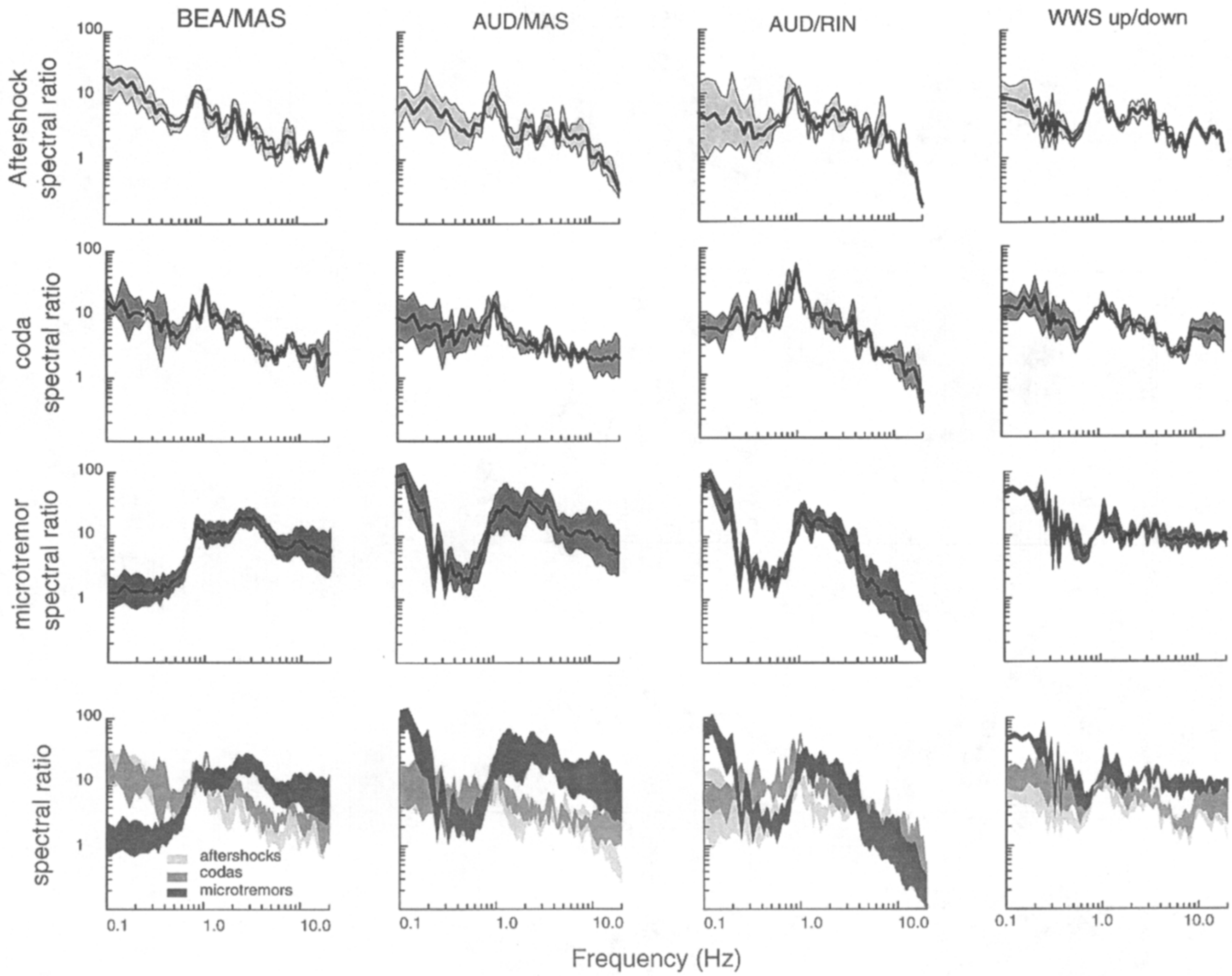

Figure 4. Average station-pair spectral ratios. The shaded area represents plus/minus one standard deviation.

generally consistent. Surprisingly, there is slightly more scatter in the nighttime recordings (not differentiated in Fig. 4), when there is less traffic noise. This suggests that daytime San Francisco traffic provides a consistent signal source. AUD/MAS, with 15 ratios, shows the largest standard deviations (the standard deviations in all figures are the standard deviations of the population) of the four station pairs. This may be because the distance between these stations is greater than that for any of the other station pairs, so the sites may be responding to different sources. The four microtremor ratios at WSS show the least scatter of all the station pairs.

The bottom row of Figure 4 shows the average microtremor, *S*-wave, and coda station-pair spectral ratios plotted together to make it easier to compare them. Agreement of the three methods varies from pair to pair. The shapes of the *S*-wave ratios are similar to the coda ratios at each station pair. The coda amplifications are higher than the *S*-wave amplifications at BEA/MAS, AUD/RIN, and WSS uphole/downhole. Aki (oral comm.) suggests that the use of a long *S*-wave window, which includes the large early coda, should result in codas and *S* waves showing similar amplifications. This is not the case at BEA/MAS and AUD/RIN. The WSS uphole/downhole coda and *S*-wave ratios are about the same at the 1-Hz peak; but elsewhere in the part of the record for which the instruments are considered reliable ($f > 0.4$ Hz), the coda values are higher by a factor of 2 to 3.

The microtremor ratio shapes are not similar to those of the earthquake ratios, except at WSS uphole/downhole. At BEA/MAS, AUD/RIN, and AUD/MAS, the microtremor spectral ratios have amplified peaks near the fundamental frequency of the *S*-wave ratios, but the width and amplifications differ. At the WSS uphole/downhole pair, the spectral shapes are similar, but the microtremor spectral ratios are twice as amplified.

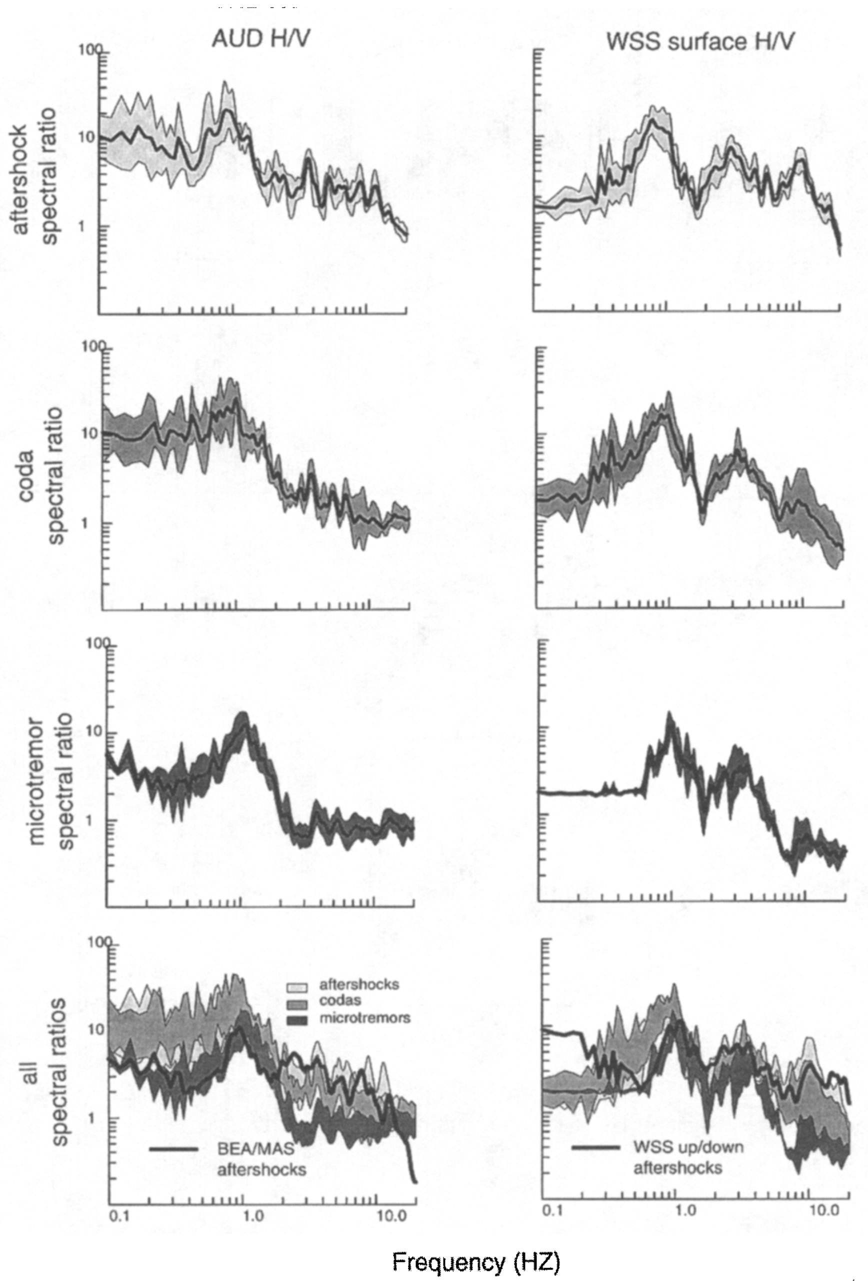

Figure 5. Average horizontal/vertical spectral ratios for soft-soil stations. The shaded area represents plus/minus one standard deviation.

Results for H/V Ratios at a Single Station (Nakamura's Method)

Horizontal/vertical spectral ratios at AUD and the surface instrument at WSS are shown in Figure 5. We are primarily interested in the microtremor ratios, but we show the aftershock H/V ratios as well. With the exception of peaks near 1 Hz, the microtremor ratios for the surface instrument at WSS bear little resemblance to the microtremor ratios for the downhole/uphole pair. The 1-Hz uphole/downhole peaks have amplitudes about twice those in the surface instrument horizontal/vertical ratios. The microtremor ratios at AUD both show the 1-Hz peak, with lower values for the H/V ratio.

In order to compare Nakamura's method to traditional station-pair analysis, the average S-wave spectral ratios for the station pairs AUD/RIN and WSS uphole/downhole are also shown as solid lines in the bottom row of Figure 5. At AUD and WSS, the frequencies of the peaks in the S-wave, coda, and microtremor horizontal/vertical spectral ratios are similar up to about 2 Hz and 6 Hz, respectively. In both cases, the S-wave and coda ratios show similar amplitudes, generally higher than the microtremor ratios.

Microtremor H/V ratios for two bedrock stations, WSS and MAS, are shown in Figure 6. Both curves are approximately flat, with an amplification of about 50%. The bedrock data illustrate that Nakumura's method of analyzing microtremors failed to produce a peak at stations where we did not expect one. The data also demonstrate the similarities between a surface bedrock station and a nearby borehole bedrock station.

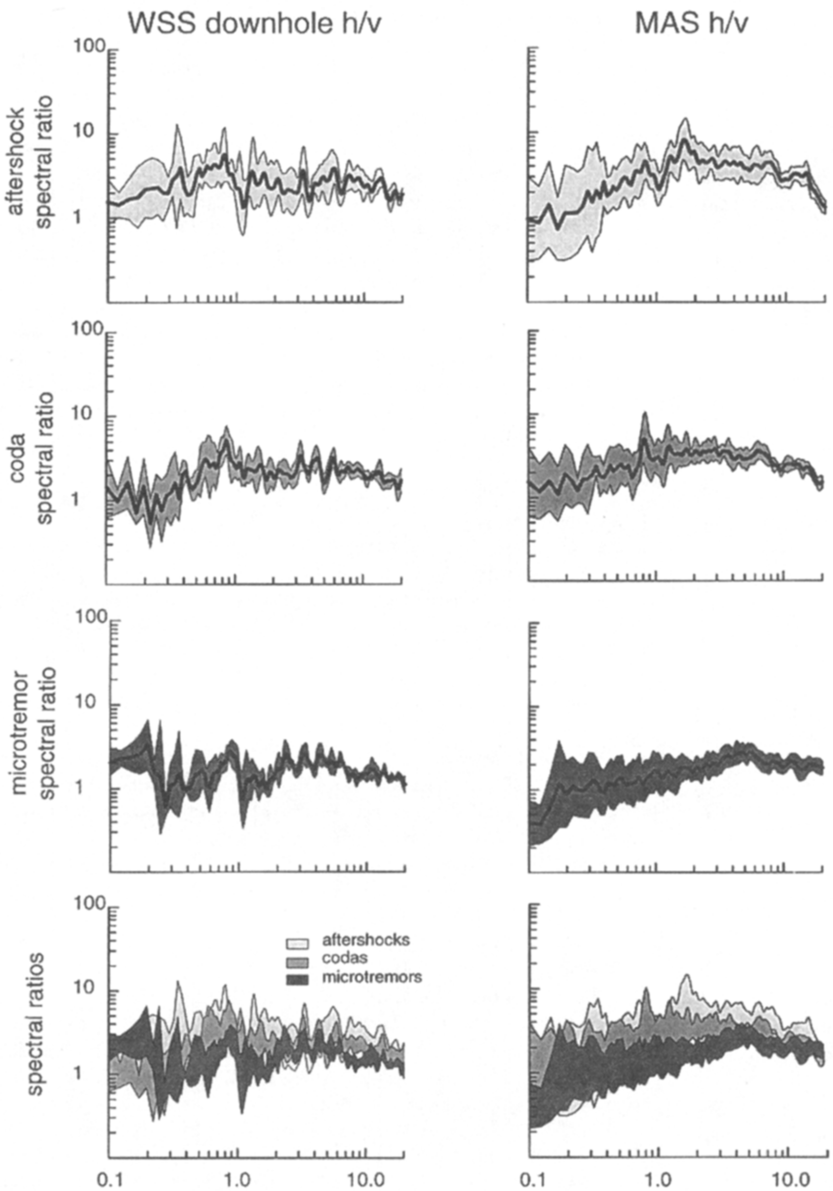

Figure 6. Average horizontal/vertical spectral ratios for two rock stations. The shaded area represents plus/minus one standard deviation.

Conclusions

Using the traditional station-pair method of analyzing seismic records, microtremor spectal ratios agree poorly with *S*-wave spectral ratios. Microtremor station pairs may be of some use for identifying the frequency of the fundamental resonance at a soil site, but our comparisons show them to be unreliable for predicting either the amplitude or the width of this resonant peak. Coda spectral ratios often show slightly more amplification than *S*-wave spectral ratios, even for the 20-sec windows used in this study.

Using Nakamura's method to analyze earthquake data gives ratios that are similar to *S*-wave station-pair spectral ratios at a range of frequencies: 0.1 to 2.0 Hz at AUD (compared with AUD/RIN) and 0.6 to 5.0 Hz at WSS uphole (compared with WSS uphole/downhole). Nakamura's method, applied to microtremors recorded at soil sites, adequately predicts the fundamental frequency observed from aftershock *S* waves at soil/rock station pairs. Nakamura's method, applied to a surface rock site and a downhole rock site, yields slight amplification without pronounced peaks.

Recent studies differ on the issue of whether Nakamura's method can be used to predict amplification in addition to the fundamental frequency (e.g., Lermo and Chavez-Garcia, 1993, 1994) or frequency only (e.g., Field *et al.,* 1995.) This study shows Nakamura's method resulting in amplifications that are similar to those derived from the *S*-wave station-pair ratios.

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