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SITE AMPLIFICATION IN THE SAN FERNANDO VALLEY FROM WEAK- AND STRONG-MOTION DATA

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ABSTRACT

During the months that followed the 17 January 1994 M6.7 Northridge, California earthquake, portable digital seismic stations were deployed in the San Fernando basin to record aftershock data. One of the goals of this deployment was to estimate site amplifications factors. About 1178 waveforms from 38 aftershocks ranging from M3.0 to M5.1, and depths from 0.2 to 19 km were recorded and analyzed at 31 three-component stations. The instrument response was removed from all the waveforms. After studying the coda Q_c decay, the site amplification was calculated taking the spectral ratio between the spectrum at different sites of the Northridge portable array with respect to the spectrum at the station LA00 which is located on rock. The used portions of the seismograms were 5 s window of the coda from velocity records, and 10 s window from the beginning of the S-wave arrival as well as 40 s window containing most of the whole record, both from acceleration records. The horizontal components were treated as a complex signal before taking the Fourier transform. The spectral ratios from the 10 s on the S-wave and 40 s on the whole record are similar. The spectral ratios from the vertical components on the coda window consistently overestimate the amplification obtained from the horizontal components on the coda window within a factor of two. The spectral ratios from the horizontal components on the coda window and those from the S-wave are similar within a factor of two. Finally, the spectral ratios from the vertical components on the coda window overestimate the amplification with respect to those from the S-window in some cases by a factor greater than two.

KEYWORDS

Strong motion seismology; site amplification; spectral ratios; coda amplification; S-wave amplification.

INTRODUCTION

It is known that each soil type responds differently when it is subjected to ground motion from earthquakes. Usually the younger softer soils amplify ground motion relative to older more competent soils or bedrock. The most frequent empirical technique used for site response estimation has been the spectral ratio method, which considers the ratio between the spectrum at a site of interest with respect to the spectrum at a reference site, usually a nearby rock site. Commonly, coda-wave ratios are used to predict the amplification (Phillips and Aki, 1986; Chin and Aki, 1991, Mayeda et al., 1991; Fehler et al., 1992; Koyanagi et al., 1992; Kato et al., 1995). The coda waves are popular with researchers due to the abundance of data provided by micro-earthquake observation networks and because the coda power spectrum can be separated into source, site, and path effects. Conversely, recordings of the direct S-waves often consist of a more limited data set, because the micro-earthquake observation networks can be saturated during the strongest part of the ground motion. In addition, many of the stations in these networks consist of only a single-component high-gain vertical sensor, which is not optimally oriented to record direct S-waves. However, during recent years, with more instrumentation and new events, seismologists have been studying the spectral ratio using S-waves (Hartzell, 1992; Field et al., 1992; Steidl, 1993; Field and Jacob, 1995; Margheriti et al., 1994; Gao et al., 1995; Kato et al., 1995). In spite of this large number of studies, seismologists are still debating which method gives better results. Recently, Margheriti et al. (1994), Kato et al. (1995), and Steidl et al. (1995) have found that the coda method overestimates the spectral ratio by a factor of 1.5 to 2.0 compared to the direct S-wave spectral ratio. In this study, the coda spectral ratio using both vertical and horizontal components, the S-wave spectral ratio using the horizontal components, and the whole record spectral ratio using the horizontal components are examined to compare these diffrent methods. In order to evaluate the differences between the methods, the uncertainties of each method have also been estimated.

DATA

In this study 38 aftershock records from the Northridge earthquake were analyzed. Figure 1 shows the location of the events as well as the stations used. All of these aftershocks present the best solution for their hypocentral location and have magitudes from 3.0 up to 5.1, and focal depths between 0.2 and 19.0 km. Thirty one stations, with 6 data channels each, were used to estimate the site amplification in the San Fernando Valley and the surrounding mountains. The stations in this study were composed primarily of the SCEC portable deployment, TERRascope stations, and Southern California Seismic Network Stations (SCSN). All the velocity sensors were three components consisting of L4-C (1.0 Hz natural frequency), L22 (2.0 Hz natural frequency), CMG3T (3.3E-02 Hz natural frequency), STS2 (8.0E-03 Hz natural frequency), and STS1 (4.0E-03 Hz natural frequency). The accelerometers had three components and sensors FBA23 (flat response between 0 and 50 Hz), and CMG5 (flat response between 0 and 100 Hz) (Edelman and Vernon, 1995; Wald et al., 1995). Because of this variety of instruments, the instrument response was removed from all the events, and the velocity channels were highpass filtered with a cutoff frequency of 0.5 Hz.

METHODS

The spectral ratio approach of dividing the spectrum at the site of interest by a nearby "reference" site to estimate the site response is used. The spectral ratios for different portions of the seismograms are computed and compared to each other. The instrument response is removed from the data before any analysis is done. The geology of the basin and the source locations directly below them make the choice of a reference site problematic. The station LA00 was selected as a reference site because it is located on rock. The calculated amplification (or deamplification) are therefore relative to the station LA00.

Coda Spectral Ratios

Before performing the coda spectral ratios, a study of the coda decay over the area was done. The lapse time for the coda window should be long enough such that the seismic energy can be assumed to be uniformly distributed under the sites of interest. The lapse time was set as three times the travel time of the S-wave of the farthest station in each event, as suggested by Margheriti et al. (1994). The spectral amplitudes for 5 s windows with 25% overlap were used for different lapse times in order to compute Q_c. Figure 2 shows the averaged Q_c for all stations and components. It is observed that there is a common decay in the San Fernando basin at this lapse time. In addition, the three components have almost the same decay. However, it is also observed that there is scattering in the values of Q_c, suggesting that a larger lapse time might be needed to more accurately determine the average value of Q_c for the whole area probably because of the geological complexity of the San Fernando basin. To calculate the spectral ratios, a window of 5 s from the coda was extracted, and a 5% Hanning taper was applied to the record. The horizontal components were treated as a complex signal, as proposed by Tumarkin and Archuleta (1992). This method calculates the Fast Fourier Transform just once regardless of the orientation of the components, and provides the maximum amplitude of shaking in the horizontal plane. The vertical component is still treated as a real signal. Before taking the spectral ratio, a smoothing procedure was applied to the spectra of the station pairs in order to avoid holes and peaks which can alter the final ratio. The smoothing was done using a box car of 0.5 Hz. Moreover, the spectra are interpolated to the same frequency interval since the sampling rate is different for each station. Once the spectral ratio for each station and each earthquake is obtained, the logarithmic average and the 95% confidence limits with respect to the mean are calculated.

S-wave and Whole Record Spectral Ratios

Two time windows were considered for the calculation of the Fourier spectrum, in order to estimate the effect of time window length on the spectral ratio. In both cases, only the horizontal components of the acceleration records were used because they have the largest amplitude of the ground motion. As for the coda method, the horizontal components were treated as a complex signal (Tumarkin and Archuleta, 1992). A window of 10 s starting 2 s before the S-wave was extracted, and then a 5% Hanning taper was applied. The spectra was smoothed and reinterpolated to a common frequency interval, and then the spectral ratio was calculated. The second time window consisted of 40 s of the record, starting 1 s before the beginning of the P-wave. Again a 5% Hanning taper was applied and the spectrum was smoothed and reinterpolated before taking the spectral ratio. The spectra of the data were corrected for geometrical spreading by multiplying each spectrum by its corresponding S-P time. Finally, the logarithmic average and the 95% confidence limits are calculated over the population of events per station.

DISCUSSION AND CONCLUSIONS

The goal of this study is to compare the methods for estimation of the site amplification factor. The spectral ratio for each method was averaged over seven center frequencies. A bandwith of +/- 0.25 Hz was used for the center frequency at 0.75 and 1.0 Hz, +/- 0.5 for the center frequency at 1.5 and 2.0 Hz, and +/- 1.0 for the remaining center frequencies at 3.0, 4.0, and 6.0 Hz. Then the averaged amplifications were plotted for different possible combinations between the methods for all frequencies and each center frequency. Figures 3 to 6 summarize the results. The solid line shows a 1:1 correspondence between methods, and the dashed lines show a factor of two of difference between methods. The vertical and horizontal bars represent the 95% confidence limits for both methods at the same center frequency.

Figure 3 shows the amplification factors obtained from the whole-record (WH) and the S-wave (SH). Since shear waves typically show greater amplification at sediments, and usually cause the most damage of man-made structures, many previous studies use S-waves for estimating the site amplification factor. However, the signal must be long enough so that any resonant peaks in the spectral ratios can be adequately resolved. Therefore, it is necessary to use as much of the signal as possible in order to achieve better spectral resolution. Nonetheless, the longer the signal segment involved, the more scattering and reflections are taken into account. This complicates a single model of site amplification for a fixed incidence angle, wave type, and azimuth. However, for seismic hazard evaluation purposes, this might be an advantage because the spectral ratio would represent a smoothed average of the site amplification over those parameters (Field et al., 1992). The values in Figure 3 remain mostly on the 1:1 correspondence. This result indicates that there is no statistical difference between 10 s and 40 s time-windows for calculating the site amplification. This suggests that there is not much contribution of the P-wave and surface waves to the record. For this reason, the remaining comparisons will be done with respect to the 10 s time window for the S-wave.

Figure 4 shows the comparison between site amplification obtained from the coda-window on the vertical component (CV) and the coda-window on the horizontals (CH). The amplification obtained from the vertical component is consistently larger than that obtained from the horizontal ones, up to and even exceeding a factor of two. This behavior is observed for all frequency ranges.

Figure 5 shows the amplification factors obtained from the coda-window (CH) and S-window (SH) on the horizontal components. The coda method and the S-wave method produce the same result within a factor of two. In Figure 6 the vertical coda-window (CV) and the horizontal S-window (SH) are plotted. The coda method estimates are larger than the S-wave method, especially above 3.0 Hz. Figure 6 shows that the coda method on the vertical component and the S-wave method do not produce the same result. In fact, the coda method consistently overestimates the site amplification factors with respect to those obtained from the S-wave method. This result was also shown in Margheriti et al. (1994) and Steidl et al. (1995) where they found amplifications generally higher for the coda-wave estimates. In addition, studies which predict strong ground motion based on vertical coda-wave amplification factors may be overestimating the predicted ground motion.

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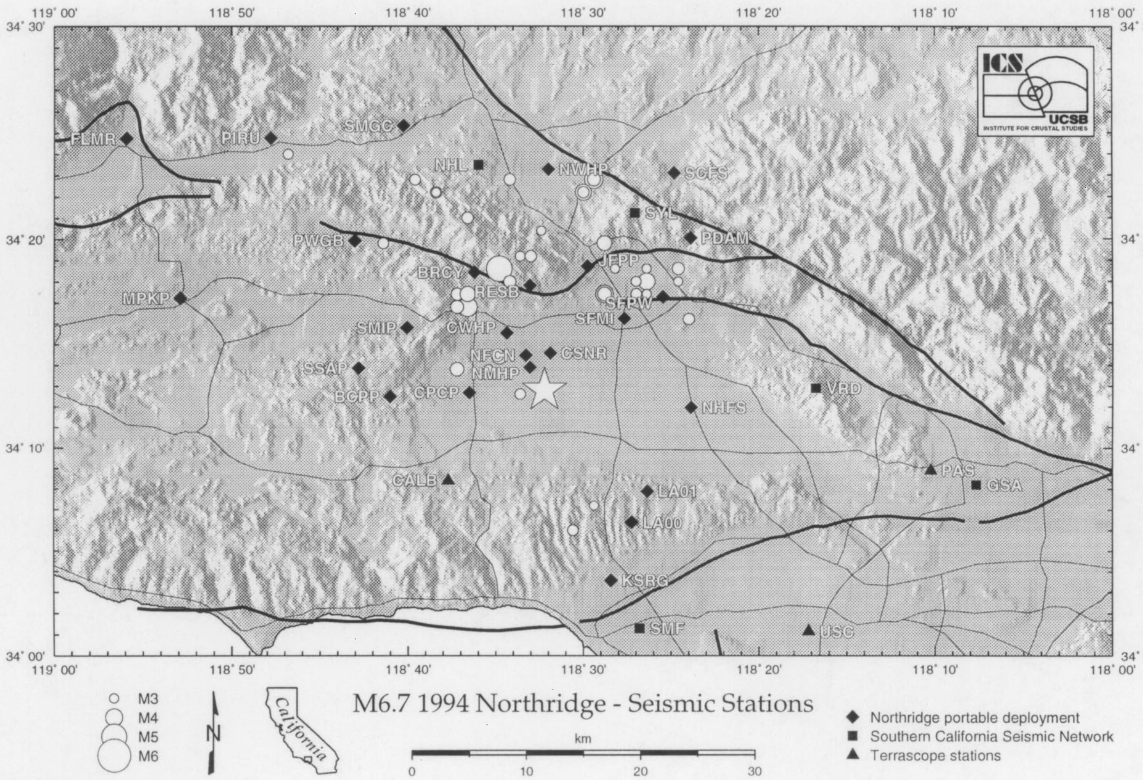

Figure 1: Regional map showing the epicenters (solid circles) and recording sites (Portable deployment - solid diamonds, SCSN - solid squares, and TERRascope stations - solid triangles) used in this study.

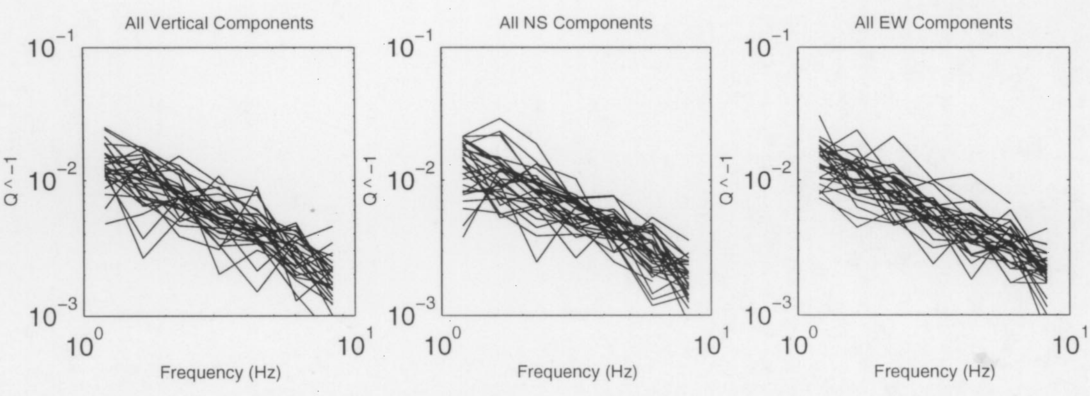

Figure 2: Coda Q_c^{-1} vs. frequency. The lapse time is three times the travel time of the S-wave at the farthest station. The value of Q_c^{-1} is an average over all the events and per station. Note that the three components have almost the same decay, but the coda Q_c^{-1} values are still not completely stable for the chosen lapse time. This suggests that there is still energy in the coda-window produced by surface waves and reverberations due to the complexity of the geology of the San Fernando basin.

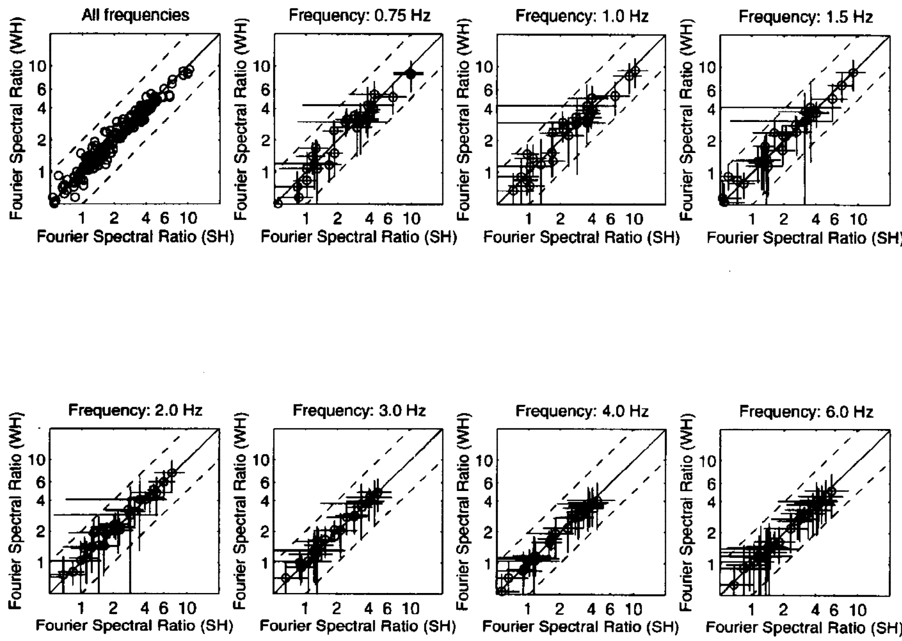

Figure 3: Amplification from horizontal whole record vs. amplification from horizontal S-window for all center frequencies (0.75, 1.0, 1.5, 2.0, 3.0, 4.0, and 6.0 Hz). The solid line represents the 1:1 correspondence between the two methods, and the dashed lines represent a factor of two of difference between methods. Also plotted are the 95% confidence limits for both methods at the same frequency. Amplifications from horizontal whole record give the same result than those obtained from horizontal S-window at all frequencies. This suggests that there is not much contribution from P-wave or surface waves to the record.

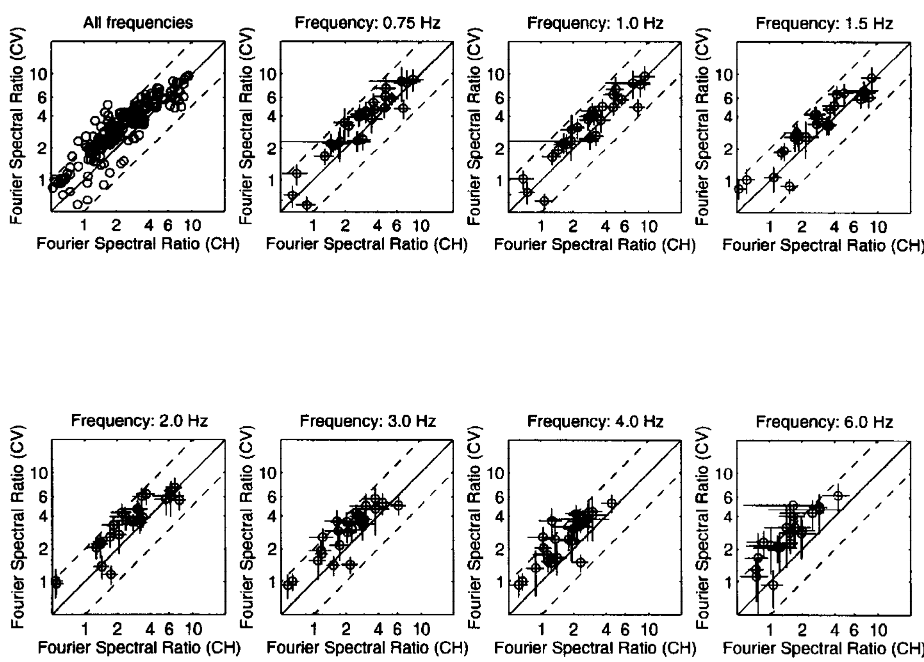

Figure 4: Amplification from vertical coda-window vs. amplification from horizontal coda-window for all center frequencies. The solid line represents the 1:1 correspondence between the two methods, and the dashed lines represent a factor of two of difference between methods. Also plotted are the 95% confidence limits for both methods at the same frequency. Amplifications from vertical coda-window consistently overestimate those obtained from horizontal coda-window within a factor of two at all frequencies.

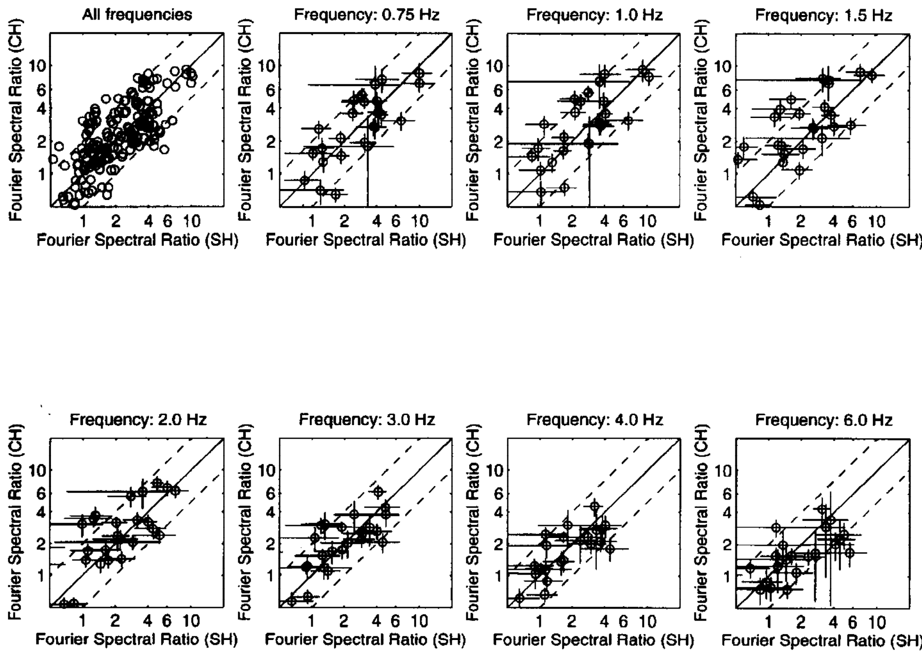

Figure 5: Amplification from horizontal coda-window vs. amplification from horizontal S-window for all center frequencies. The solid line represents the 1:1 correspondence between the two methods, and the dashed lines represent a factor of two of difference between methods. Also plotted are the 95% confidence limits for both methods at the same frequency. Amplifications from horizontal coda-window are in general similar than those obtained from horizontal S-window within a factor of two at all frequencies.

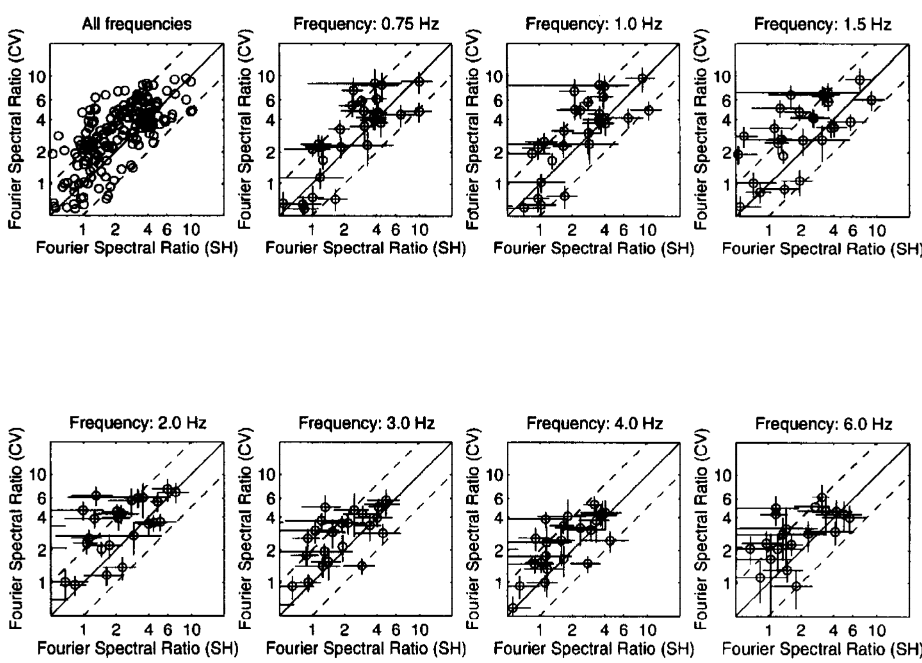

Figure 6: Amplification from vertical coda-window vs. amplification from horizontal S-window for all center frequencies. The solid line represents the 1:1 correspondence between the two methods, and the dashed lines represent a factor of two of difference between methods. Also plotted are the 95% confidence limits for both methods at the same frequency. Amplifications from vertical coda-window are in some cases more than twice larger than those obtained from horizontal S-window at all frequencies.