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Comparisons of Ground Motions from the 1999 Chi-Chi Earthquake with Empirical Predictions Largely Based on Data from California

by David M. Boore

Abstract This article has the modest goal of comparing the ground motions recorded during the 1999 Chi-Chi, Taiwan, mainshock with predictions from four empirical-based equations commonly used for western North America; these empirical predictions are largely based on data from California. Comparisons are made for peak acceleration and 5%-damped response spectra at periods between 0.1 and 4 sec. The general finding is that the Chi-Chi ground motions are smaller than those predicted from the empirically based equations for periods less than about 1 sec by factors averaging about 0.4 but as small as 0.26 (depending on period, on which equation is used, and on whether the sites are assumed to be rock or soil). There is a trend for the observed motions to approach or even exceed the predicted motions for longer periods. Motions at similar distances (30–60 km) to the east and to the west of the fault differ dramatically at periods between about 2 and 20 sec: long-duration wave trains are present on the motions to the west, and when normalized to similar amplitudes at short periods, the response spectra of the motions at the western stations are as much as five times larger than those of motions from eastern stations. The explanation for the difference is probably related to site and propagation effects; the western stations are on the Coastal Plain, whereas the eastern stations are at the foot of young and steep mountains, either in the relatively narrow Longitudinal Valley or along the eastern coast—the sediments underlying the eastern stations are probably shallower and have higher velocity than those under the western stations.

Introduction

Empirically based equations are often used to predict ground shaking for use in engineering applications. Because of limited data, particularly for large earthquakes, authors of the equations usually cannot afford to be very restrictive in the geographic region or tectonic regime from which data are obtained. The most common classification scheme divides the world's earthquakes into three groups: active tectonic regions, shallow earthquakes in stable continental regions, and earthquakes in subduction zones (Abrahamson and Shedlock, 1997), the assumption being that ground motions from earthquakes in tectonically similar regions would be similar. Four commonly used sets of equations for active tectonic regions are those by Abrahamson and Silva (1997), Boore *et al.* (1997), Campbell (1997, 2001), and Sadigh *et al.* (1997). These sets of equations are largely based on data from California, but to augment the dataset for large earthquakes, all but Boore *et al.* (1997) include data from other parts of the world. This short note makes a quantitative comparison between the response spectra from ground motions of the Chi-Chi earthquake and the response spectra predicted from the four empirically based sets of equations just mentioned. I find that the observed motions differ from the predicted motions by factors larger than expected from earthquake-to-earthquake variation.

Data Selection and Processing

The ground-motion data were obtained from the CD-ROM distributed by Lee *et al.* (1999) (see also Shin *et al.*, 2000). Only the horizontal components were used. Plots of all of the uncorrected acceleration time series were inspected to identify those with noise spikes; the few that were found (north–south components at KAU022, KAU034, KAU040) were easily corrected. In addition, at HWA053, HWA054, and TTN047, one of the three channels was noisy and was not considered in the analysis.

Source-to-site distances were computed for each station. Three distance measures were used (Abrahamson and Shedlock, 1997); r_{jb}, the closest horizontal distance from the station to the projection of the rupture surface onto Earth's surface; r_{rup}, the shortest distance between the station and the rupture surface; r_{seis}, the same as r_{rup}, except that the rupture surface is assumed to extend no shallower than the seismogenic depth of 3 km. The assumed rupture surface corresponds to a preliminary model used to model the waveforms of the main shock (H. Sekiguchi, written comm., 2000). A map view of this surface is shown in Figure 1. The rupture surface consists of two planes, the larger, nonrectangular one dipping 29° to the east, and the smaller, rectangular plane (to the northeast) dipping 5° to the east and abutting the lower edge of the larger plane.

Stations were excluded from the analysis if $r_{\mathrm{seis}} > 60$ km; this is the distance criteria used by Campbell (1997) in his prediction equations. The resulting stations are shown in Figure 1, with different symbols for stations corresponding to different ranges of the distance measure r_{rup}.

The average of a portion of the preevent portion of each acceleration time series was removed from the whole record, and the 5%-damped response spectra for periods up to 20 sec were computed from these corrected records. Further baseline corrections and/or filtering are necessary if peak velocity and peak displacements are required, but the comparisons in this note are only for response spectra. Boore (1999, 2001) shows that these further corrections do not influence the response spectra for periods less than about 20 sec. For comparison with the predicted equations, the geometrical mean of the response spectra for the two horizontal components at each station was computed.

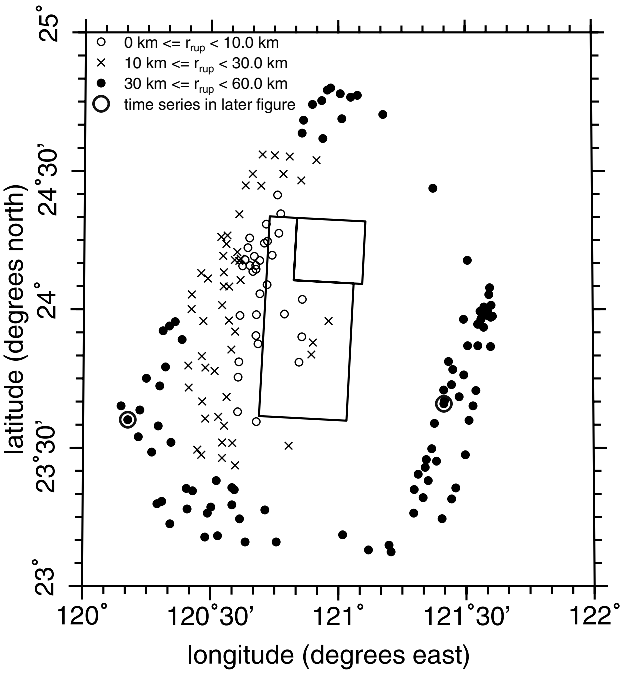

Figure 1. A map of the stations, with the three distance bins used in computing average residuals indicated by different symbols (see legend). Time series for the two stations surrounded by a circle are shown later in this article. The map view of the assumed rupture surface is shown by the lines; stations within the lines defining the edges of the rupture have $r_{\mathrm{jb}} = 0.0$ and are stations for which Abrahamson and Silva's (1997) hanging-wall factor is applied in predicting the motions, using their equations.

Prediction of Motions and Residuals

The basic procedure was to compute the predicted motion for each station and then form the ratio of observed to predicted motions. Because the predictions are in terms of the logarithms of the spectra, a residual is defined as the difference of the logs of the observed and predicted motion; this is the same as the log of the ratio of the observed and predicted motion. For this reason I use the terms *ratio* and *residual* interchangeably. The residuals were then grouped into three distance bins, and a geometric average of the residuals for each prediction equation was computed for all residuals in each bin.

As mentioned earlier, predictions from four equations were used: Abrahamson and Silva (1997), Boore *et al.* (1997), Campbell (1997, 2001), and Sadigh *et al.* (1997). These equations have as predictor variables the magnitude of the earthquake, the distance to the station, and some measure of the type of site. All equations use moment magnitude (**M** 7.6 for this application), but the other variables are not the same for each equation. I have used the appropriate distance measure for each prediction equation. Unfortunately, I had no information about the geologic conditions at each site, so I computed two sets of residuals; one assuming that all stations were rock and one assuming that all stations were soil. The prediction equations of Abrahamson and Silva (1997) and Sadigh *et al.* (1997) only have two site categories—rock or soil—so no assumptions had to be made in computing the predicted motions. In the prediction equations of Boore *et al.* (1997), however, the geologic condition is specified by the average velocity to 30 m (V_{30}). For soil and rock predictions, V_{30} was set to 310 and 620 m/sec, respectively (Boore and Joyner, 1997). Campbell's recommendations (Campbell, 2000) for his soft rock (S_{SR}), hard rock (S_{HR}), and depth to basement (D) variables were followed for predictions of rock and soil motions using his equations. These are as follows: for rock motions, $S_{\mathrm{SR}} = 1$, $S_{\mathrm{HR}} = 0$, and $D = 1$ km; for soil motions, $S_{\mathrm{SR}} = 0$, $S_{\mathrm{HR}} = 0$, and $D = 5$ km.

An example of the residuals for each station and the average residual in each distance bin is shown in Figure 2. As is usual with strong-motion data, there is a considerable amount of scatter, but the mean of the residuals shows a clear bias corresponding to overprediction of the motions.

Average Residuals in Distance Bins

To better look for trends, from here on I only discuss average residuals. Plots of the average residuals for the dis-

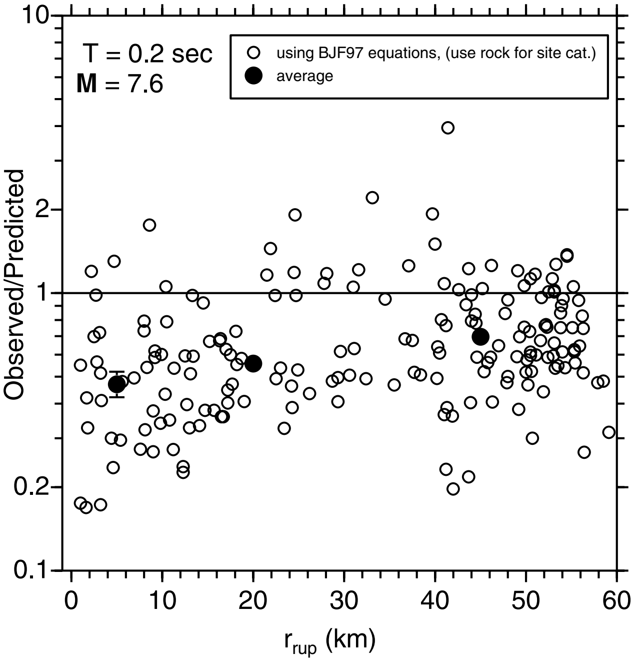

Figure 2. The ratio of the observed response spectra for 0.2-sec oscillator period and predictions from the Boore *et al.* (1997) equations, assuming rock (V_{30} = 620 m/sec). Open circles are for individual stations, and the larger filled circles are geometrical means (with the standard error of the mean) for the residuals in three distance bins (as indicated in Fig. 3).

tance bins are plotted against oscillator period (T) in Figure 3 (the average residual for peak acceleration is plotted at T = 0.02 sec). The general conclusion from this figure is that the Chi-Chi ground motions are smaller than the predicted motions for periods less than about 1 sec by factors averaging about 0.4. There is a tendency for the residuals to be less negative as distance increases, which might indicate differences in the regional attenuation of ground motion in Taiwan and in California. Of course, because of interearthquake variability, it would be very unusual if the residuals varied around a value of 1.0. Interearthquake variability found by Boore *et al.* (1997) is too small, however, to explain the observed deviation of the residuals from unity shown in Figure 3 (Boore *et al.* find the interearthquake component of variance to be period dependent, going from a factor of 1.0 at T = 0.1 sec to a factor of 1.3 at T = 2.0 sec).

There is a trend for the observed motions to approach or even exceed the predicted motions for longer periods. The comparison of the observed and predicted motions, however, is handicapped by the lack of information regarding geologic conditions at the sites. If they were all soil sites, then observed motions are smaller than the predicted for almost all periods and distances. In reality, of course, the sites are probably a mix of rock and soil sites.

Residuals for Western and Eastern Groups of Stations

The residuals in the 30- to 60-km distance bins seem to have less of a trend with period than do the residuals in the other distance bins. In addition, the stations in the 30- to 60-km distance bin are probably all on soil. The stations to the west and southwest of the fault are situated on the Coastal Plain, whereas those to the east and southeast are either in the fault-controlled Longitudinal Valley or along the coast at the base of the Coast Range (Ho, 1988). It is reasonable to expect that the soils underlying the eastern and western stations are different, with thicker and finer-grained soils under the western stations and coarser-grained (and thus higher velocity) and thinner soils under the eastern stations (H.-P. Liu, oral comm., 2000). For this reason I computed average residuals for two groups of stations: the western group, with latitudes less than 24.33 degrees and longitudes less than 121.00 degrees, and the eastern group, with latitudes less than 24.33 degrees and longitudes greater than 121.00 degrees. The average residuals are shown in Figure 4, from which it can be seen that they are similar except for the very longest oscillator periods. To better see the relation, the ratio of the average residuals are shown in Figure 5 (the residuals were computed assuming soil in the prediction equations, but almost identical results are found if ratios are computed assuming rock in the prediction equations). The ratio of residuals for the east and west groups is near unity except for periods longer than about 2 sec, beyond which the ratio of residuals increases rapidly with period.

Because the predictions do not distinguish between eastern and western stations, the difference in residuals must be due to differences in the observed ground motions. To better understand the differences, I looked at the time series for the two groups of stations. The clear conclusion is that the western stations have long-duration, long-period oscillations that are not seen on recordings at the eastern stations. These differences are obvious on the accelerograms but are more dramatic in the displacement time series. Representative examples are shown in Figure 6 (the stations are indicated in Fig. 1 by circles). The time series shown in this article are representative of the differences in wave content, but I have deliberately chosen stations for which the recording durations were long in order to better see the overall behavior of the motions (these motions are from the IDSA instruments; the A900 instruments generally cease recording after 90 sec). I used the standard processing employed by the National Strong Motion Program of the U.S. Geological Survey (see *http://nsmp.wr.usgs.gov/processing.html* for details) to remove a baseline and to filter the data with a fourth-order causal butterworth filter with corner of 0.02 Hz before integrating to displacement. The differences in waveforms between the eastern and western station are obvious and dramatic. The response spectra for the accelerograms at the two stations are shown in Figure 7, after multiplying the spectrum from HWA005 by 0.7 so that the spectra from both

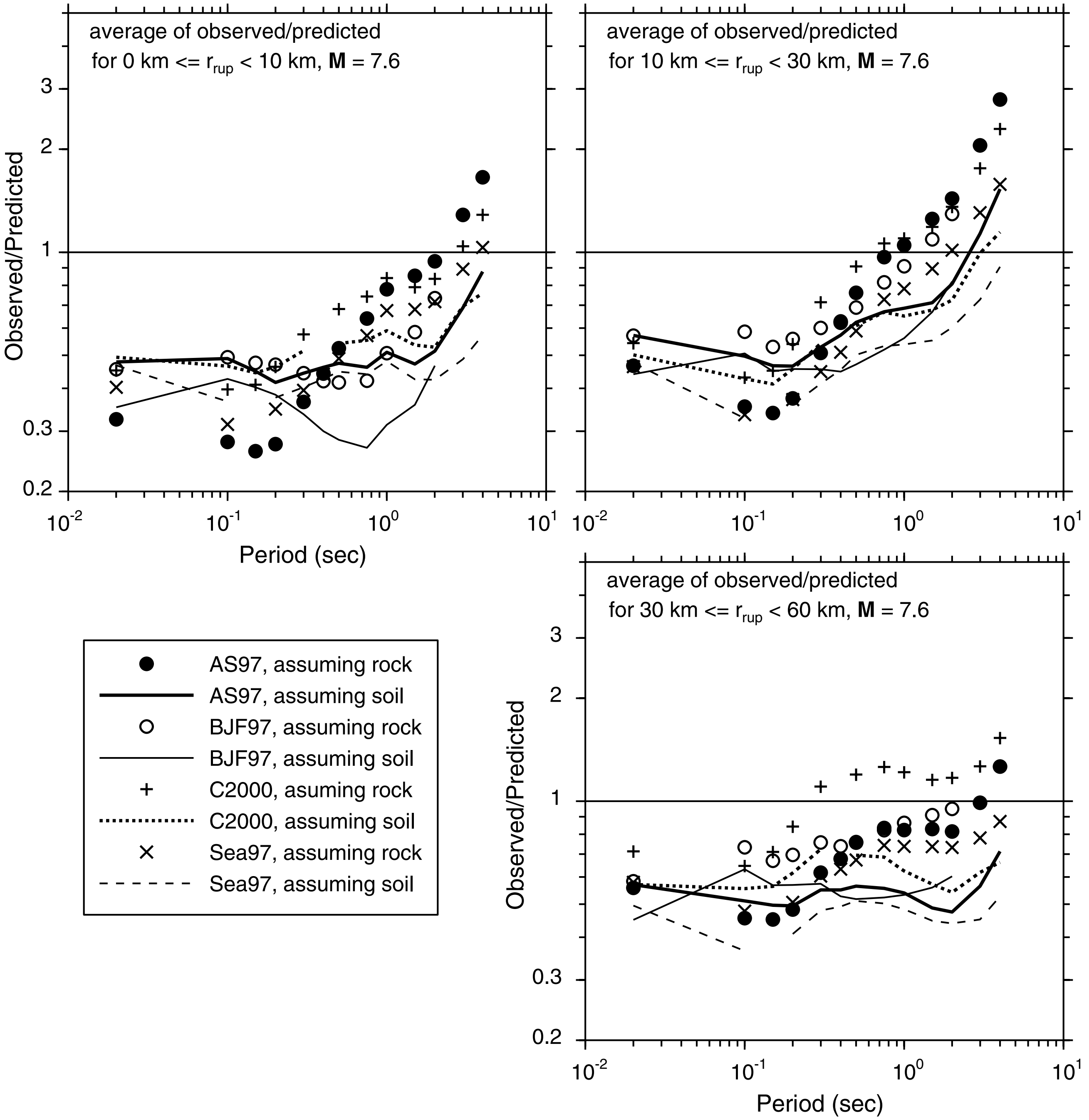

Figure 3. Mean residuals plotted against oscillator period (with the residual for peak acceleration plotted at $T = 0.02$ sec) for three distance groups and for the four prediction equations, assuming either rock or soil site conditions in the prediction equations.

stations are similar in amplitude at short periods. The response spectra are very similar for period less than about 2 sec, but between 2 and 20 sec, the response spectrum of the station to the west is up to five times larger than that from the station to the east. While the longer duration motions for the western stations are probably surface waves propagating across the Coastal Plain, the differences in the response spectra are largely controlled by motions within the first 90 sec (compare pluses and open circles in Fig. 7).

Conclusions

The comparison of observed motions and those predicted from prediction equations largely based on ground motions from California finds that short-period motions from the Chi-Chi earthquake are generally smaller than the predicted motions for periods less than about 1–2 sec, regardless of what prediction equation is used and whether it is assumed that the site is underlain by rock or by soil. The observed motions differ from the predicted motions by factors larger than expected from earthquake-to-earthquake variation. There is a trend for the observed motions to approach, or even exceed, the predicted motions for the very longest periods (4 sec). A remarkable difference is seen between what would otherwise be classified as soil sites to the east and to the west of the fault, with the western sites, on the Coastal Plain sediments, having long duration waves with periods of 5 to 7 sec. The response spectra of the two groups of stations are similar for periods less than about

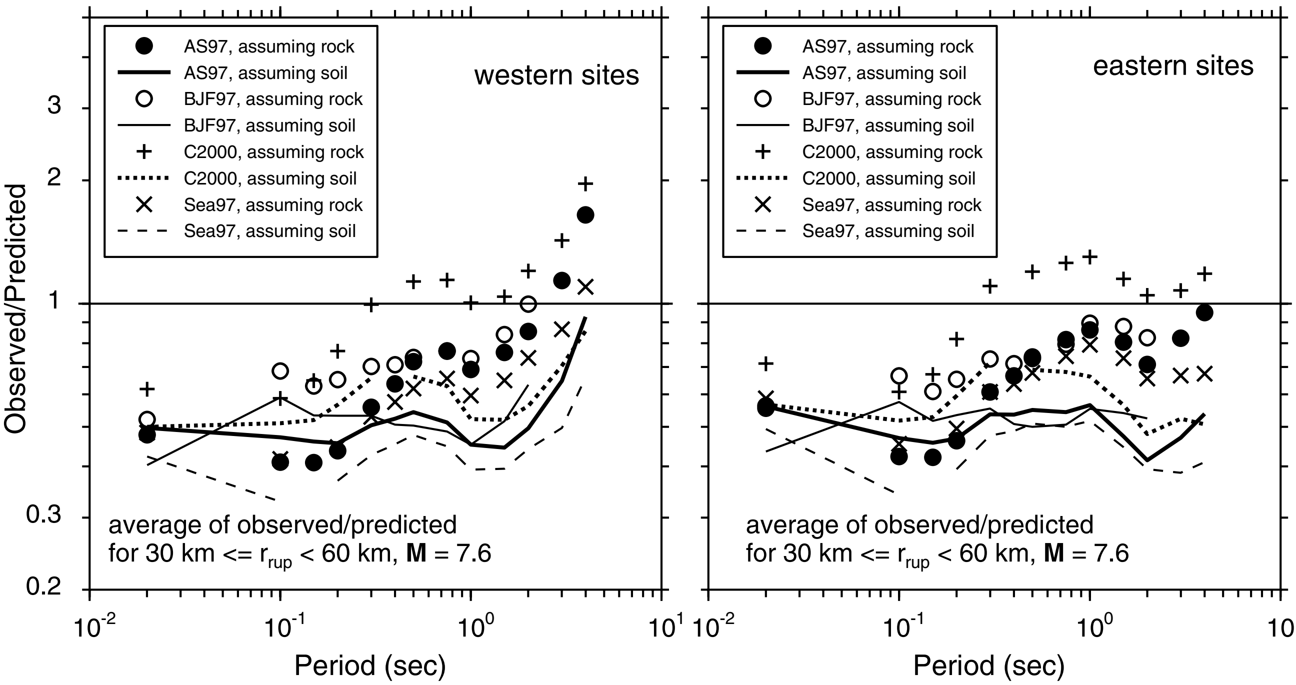

Figure 4. Mean residuals for the $30 \leq r_{\mathrm{rup}} < 60$ km bin for the east and west groups of stations (see text).

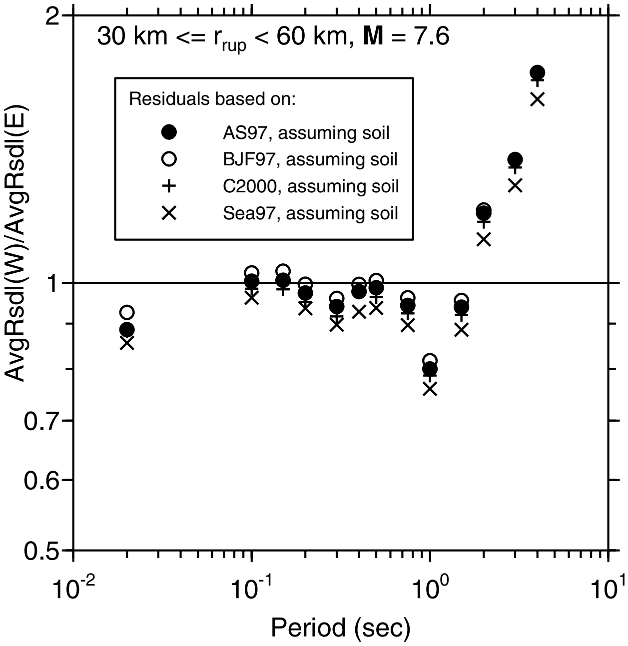

Figure 5. Ratios of average residuals for the eastern and western groups of stations (see text).

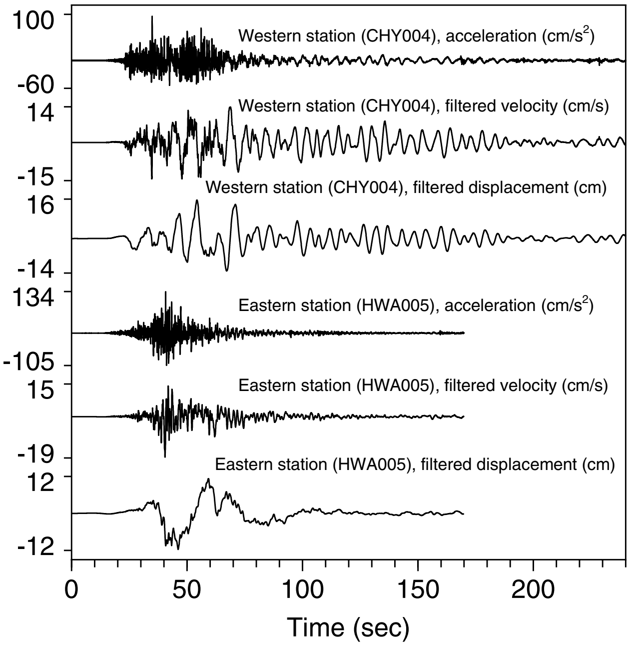

Figure 6. Acceleration, velocity, and displacement time series at stations that are representative of motions at the eastern and western groups of stations (see text).

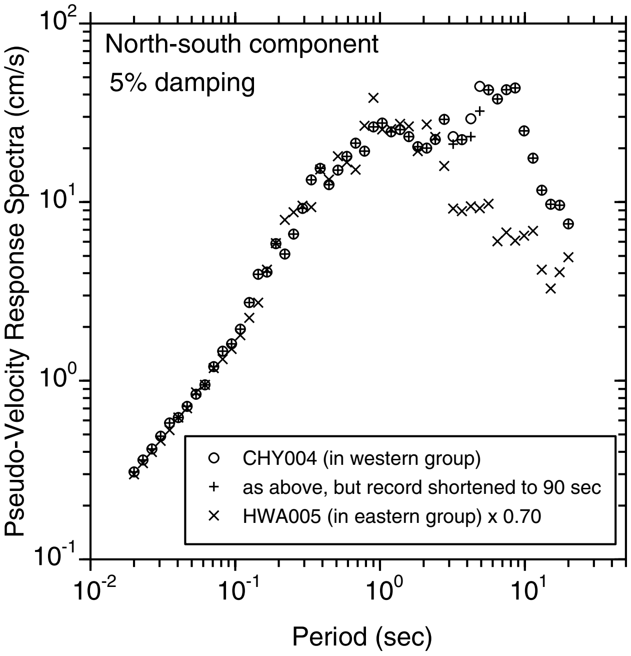

Figure 7. Direct comparison of response spectra for the motions shown in the previous figure, after normalizing by eye so that they match at short periods (this required multiplying the HWA005 spectrum by 0.7). The spectrum obtained from a truncated version of the longer-duration motion is also shown.

2 sec, but the spectra for stations on the Coastal Plain sediments exceed those from the stations to the east by factors as large as 5 at periods near 7 sec. The observed differences in the motions at the eastern and western stations are probably due to a combination of source and propagation effects, depending on the period of the motions. Distinguishing between these effects, and separating surface-wave propagation from site resonances due to nearly vertically propagating waves, is beyond the scope of this short note. No matter what the reason for the differences between motions to the east and to the west, design of structures on the Coastal Plain must consider the relative enhancement of the spectral amplitudes for sites on the Coastal Plain.

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Haruko Sekiguchi provided her preliminary estimates of the rupture surface. Hsi-Ping Liu suggested that I study the residuals of the eastern and western groups of stations separately; he also shared his thoughts about possible differences in soil conditions under the two groups of sites. I had useful discussions with a number of people, including Ken Campbell, Bill Joyner, and Willie Lee. Ken Campbell provided a preprint of his review article on prediction equations, which was very helpful in preparing the FORTRAN subroutines used to compute the motions. Helpful comments on the manuscript were provided by Bill Joyner, Hsi-Ping Liu, and Paul Spudich.

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