Empirical Constraints on Nonlinear Site Response Using Data from the 1999 Chi-chi, Taiwan, Earthquake

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Investigations Undertaken

The stochastic method for simulating strong ground motions from finite faults is applied to the records of the 1999 Chi-Chi, Taiwan, earthquake. The method is initially calibrated against the data recorded at twenty-four rock sites, located within 7-120 km from the hypocenter and providing broad azimuthal coverage of the fault. The accuracy of the simulations is quantified through the model bias, defined as the logarithm of the ratio of the observed to simulated spectrum, averaged over all stations. The calibrated model has a near-zero average bias in the frequency range from 0.1 to 20 Hz. An unusually low value is found for the radiation-strength parameter *s*, controlling the high-frequency radiation and related to the maximum slip velocity on the fault, compared with the mean value found for North American earthquakes. This result reflects the observed low-PGA character of the Chi-chi event and, physically, its lower-than-usual fault slip velocities.

The calibrated model is then used to simulate the soil-site (Class D) records under the linear-response assumption. The simulated input motions are amplified by the weak-motion amplification functions, obtained from the available aftershock records. This analysis reveals an average reduction in amplification in strong motions to about 0.5-0.6 of that in weak motions, with an approximate acceleration "threshold" for detectable nonlinearity of 200-300 cm/sec^2. However, the derivation of site-specific weak-motion amplifications is limited by the amount of aftershock data available; further quantification of the nonlinearity in soil response may be possible with the release of additional aftershock databases.

Results

<u>Model calibration</u>

The calibration was done using the finite-fault simulation code FINSIM (Beresnev and Atkinson, 1998). The rock sites used for calibration belong to NEHRP Class B ("rock") (Lee *et* *al*., 2001a); they are shown as solid triangles in Figure 1. The strong-motion data were taken from the files disseminated on CD-ROM by Lee *et al*. (2001b). The fault has dimensions of 110 x 40 km with strike of 5° and easterly dip of 36°. The fault was assigned a uniform slip distribution and discretized into 10 × 4 subfaults based on the empirical relation of Beresnev and Atkinson (2002, equation 1). We assumed a frequency-dependent $Q = 117f^{0.77}$ (Chen *et al*., 1989) and the geometric spreading $1/R^b$, where b=1.0 for R<50 km and b=0 for 50≤R<150 km (Sokolov, 2000). Simulated spectra were amplified by the generic-rock factors of Boore and Joyner (1997) and additionally attenuated by the kappa operator with κ=0.07, which was the value found from best fitting the observed spectra.

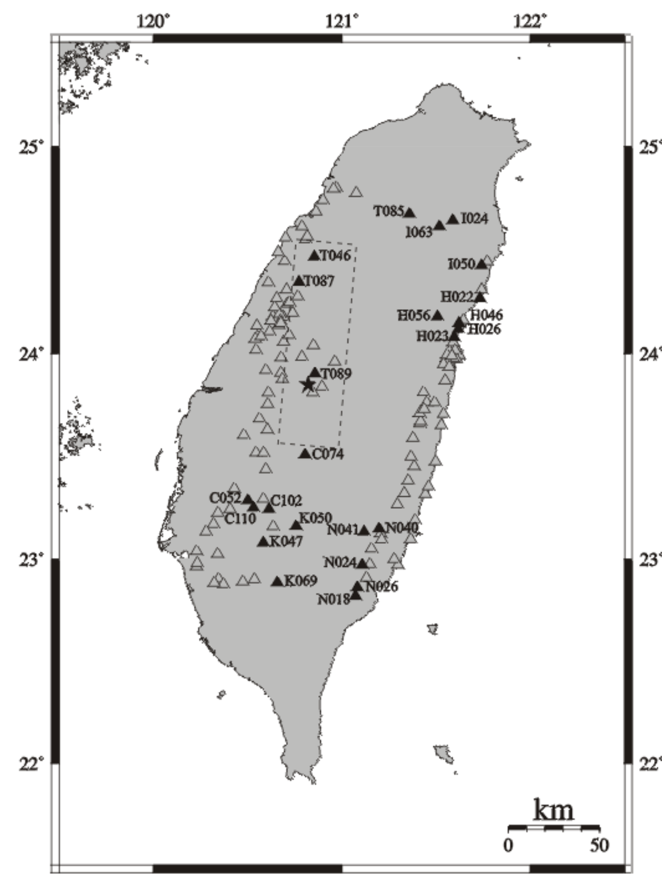

Figure 1. Rock (black triangles) and soil (gray triangles) stations used in this study. Codes are shown for rock stations. The epicenter of the 1999 Chi-chi earthquake (star), as well as the surface projection of the fault plane (dashed line) are also shown.

The radiation-strength factor *s* is the only free parameter of the model (Beresnev and Atkinson, 2002) and was determined by trial-and-error. The best fit within the examined frequency range (0.1 to 20 Hz) was provided by *s*=1.0, which is much lower than the average value estimated for North American earthquakes (*s*=1.5±0.3; Beresnev and Atkinson, 2001).

The performance of the calibrated model is demonstrated in Figure 2, where we compare the observed and simulated spectra for all twenty-four rock stations. Taking into account the complexity of the examined event, the simplicity of the model, and the fact that all rock-site responses were assumed to be unity, the fit can be considered very satisfactory.

The model bias for the rock stations is presented in Figure 3. The mean bias is within the 95% confidence limits of zero, shown as dashed lines, throughout almost an entire frequency range, showing that the model adequately predicts strong ground motions on average.

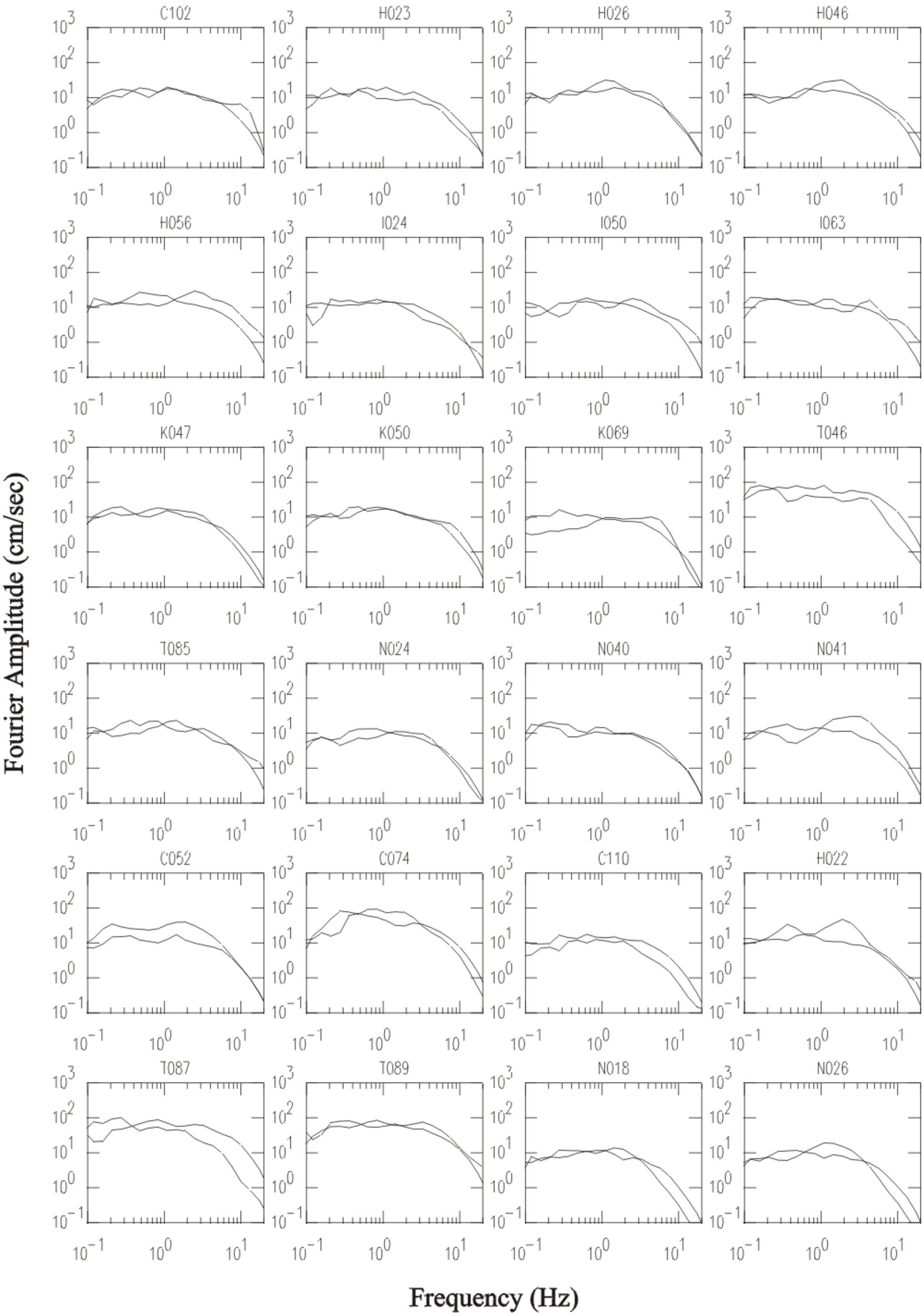

Figure 2. Comparison of observed (solid lines) and simulated (dashed lines) Fourier amplitude spectra of acceleration at twenty-four rock sites used in the calibration.

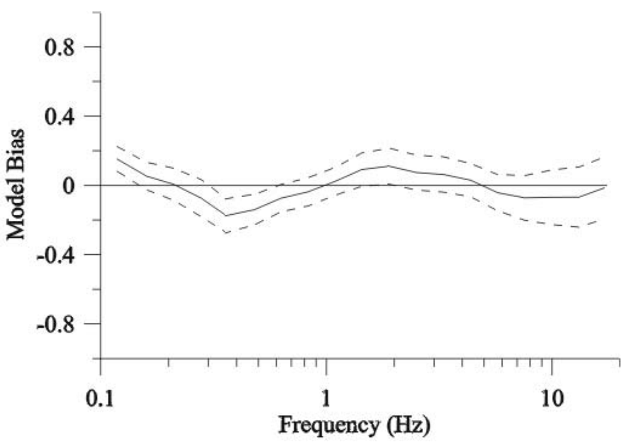

Figure 3. Bias of the calibrated model.

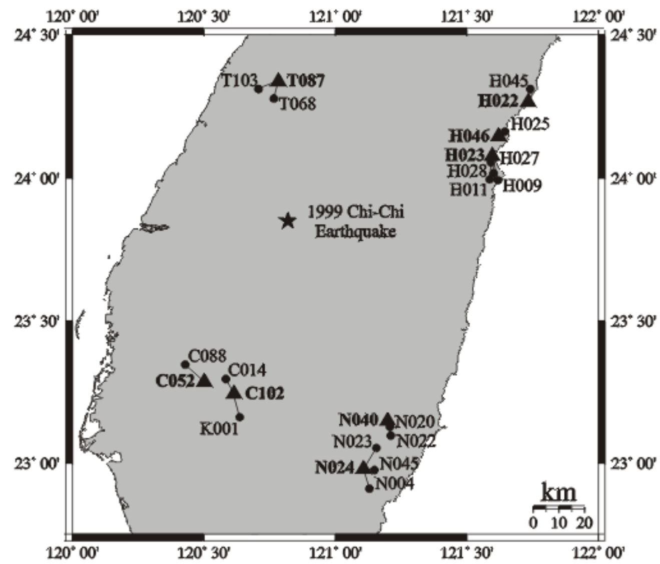

Figure 4. Locations of the stations used in the spectral-ratio analyses. The reference stations and the soil sites are shown as triangles and circles, respectively. Each soil site is connected to its reference station through a line.

<u>Application to study of nonlinear soil response</u>

The idea of the second step of the study is to apply the calibrated model to the simulation of soil records (Class D – "stiff soil"), with the exception that the predicted motions are amplified by the soil-response functions derived in the assumption of linear response. Similarly to rock sites, the prediction bias is calculated as the logarithm of the ratio between the observed and simulated Fourier spectra, averaged over all soil sites. This bias estimates the strong- to-weak-motion amplification ratio (Beresnev, 2002, equation 1). If the amplification during the main shock was equal to the weak-motion amplification, the mean soil-site prediction bias would statistically be indistinguishable from zero. However, if the bias falls below zero in a statistically significant sense, the simulated spectra exceeded the observed spectra because the observed amplification was reduced by nonlinearity. All soil stations considered below lie within the distance range of the calibrated model.

We deduce the site-specific weak-motion amplifications from the aftershock records obtained at the same soil stations that recorded the main shock, provided the same aftershocks have also been recorded by a nearby rock site. The amplifications are then calculated by the spectral-ratio technique. We inspected the Chi-chi aftershock databases released so far (Lee *et al*., 2001c,d) to find such pairs of soil and rock sites; the selection criteria included a maximum distance of 10 km between the stations in the pair and a minimum number of three aftershocks recorded at both. In total, sixteen soil sites were found to satisfy these criteria. The locations of these sites are depicted in Figure 4.

First, we applied the code to only these sixteen sites. The average model bias is presented in Figure 5a, where the dashed lines show ± 95 % confidence limits of the mean. Although an over-prediction of the observed main-shock motions appears throughout the entire frequency range, this result is at the boundary of statistical significance.

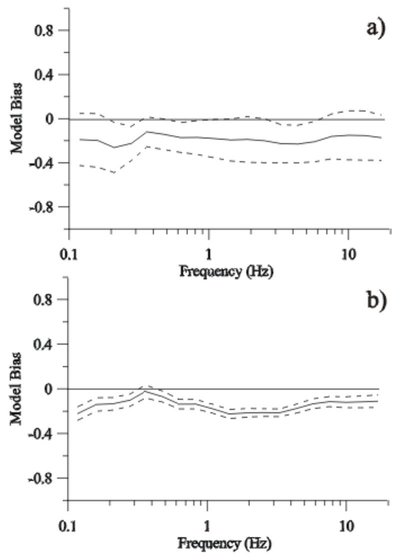

Figure 5. Bias for soil-site simulations. (a) Sixteen soil sites, for which simulated spectra were amplified by site-specific amplification functions. (b) Bias for 115 soil sites, for which average Class D empirical transfer function was used.

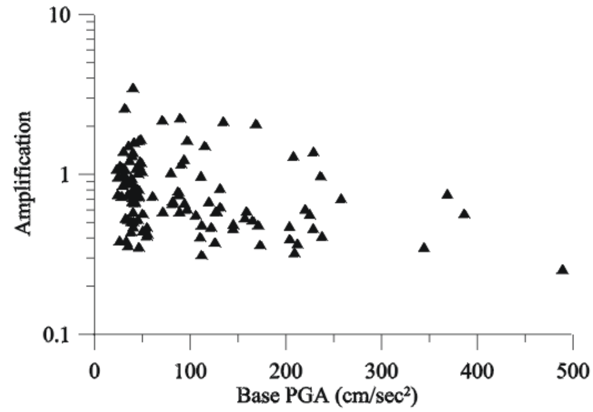

Figure 6. Ratios of strong- to weak-motion amplification at D-Sites as a function of estimated base peak acceleration.

Since the number of soil stations with empirical weak-motion responses was only sixteen, we conducted the same analysis for all Class-D stations by assigning them the average Class-D transfer function calculated from all spectral ratios obtained for the sixteen sites. In doing so we made an assumption that this average amplification would be representative of the average Class D condition in Taiwan. These stations share common geology and can be expected to cluster around a common mean amplification curve (Lee *et al*., 2001a). The model bias for all 115 Sites D is presented in Figure 5b; these sites are shown as gray triangles in Figure 1. The predicted spectral level appears to be larger compared to observations, at the 95% confidence level.

Figure 6 plots the ratio of strong- to weak-motion amplification estimated individually at the 115 sites as a function of synthetic peak acceleration at the base of soil. The results are shown for a representative frequency of 2.5 Hz. A significant scatter in the data exists, which should be attributed to the uncertainties in modeling the site-specific responses by the average transfer function, as well as in estimating PGA at the base of soil using the calibrated model. Despite the scatter, a trend is seen toward an overall decrease in the amplification ratio as the input acceleration increases. Figures 5b and 6 suggest an overall reduction in amplification in strong motions to about 0.5-0.6 of that in weak-motions, above a "threshold" acceleration level of 200-300 cm/sec^2. The value of the reduction and the threshold are consistent with recent studies of large California earthquakes. The nonlinear response appears to affect a wide frequency band, from 0.1 to 20 Hz.

Although Figures 5b and 6 reveal observable nonlinear phenomena during the Chi-Chi main shock, the picture is not as clear as one could expect from the wealth of strong-motion records that this earthquake had provided. This is primarily due to the relatively small amount of aftershock data released so far, which do not allow detailed examination of soil response at a large number of D-Sites or any of the E-Sites ("soft soil"). Future releases of additional aftershock records could help enhance quantitative character of our conclusions.

The authors are grateful to William H. K. Lee for providing us with up-to-date strong-motion databases of the Chi-chi main shock, as well as with invaluable aftershock data soon after their release.

Non-Technical Summary

The stochastic model well explains near-fault seismic data densely recorded during the catastrophic 1999 Chi-chi, Taiwan, earthquake. When validated against data on rock sites, the model accurately predicts observed seismic motions on average. A hypothesis is then tested whether the records on soil sites could be equally well predicted, in the assumption of linear elastic behavior of sediments. When applied to 115 soil stations, this hypothesis is rejected, implying that soil response has been conspicuously nonlinear. Nonlinearity reduced the amplification of ground motions by sediments by a factor of about 1.7-2 during the mainshock compared with small earthquakes.

Availability of Data

The FORTRAN code FINSIM used to simulate ground motions from the Chi-chi earthquake, along with all input files, is available upon request. Contact: Igor Beresnev, 515-294-7529, beresnev@iastate.edu.

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