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Stochastic Finite-Fault Modeling of Ground Motions from the 1994 Northridge, California, Earthquake. II. Widespread Nonlinear Response at Soil Sites

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Abstract On average, soil sites behaved nonlinearly during the *M* 6.7 1994 Northridge, California, earthquake. This conclusion follows from an analysis that combines elements of two independent lines of investigation. First, we apply the stochastic finite-fault simulation method, calibrated with 28 rock-site recordings of the Northridge mainshock, to the simulation of the input motions to the soil sites that recorded this event. The calibrated model has a near-zero average bias in reproducing ground motions at rock sites in the frequency range from 0.1 to 12.5 Hz.

The soil sites selected are those where there is colocation of strong-motion accelerographs and temporary instruments from the Northridge aftershock observation network. At these sites, weak-motion amplification functions based on numerous aftershock records have been empirically determined, in three separate investigations reported in the literature. These empirical weak-motion amplification factors can be applied to the simulated input rock motions, at each soil site, to determine the expected motions during the mainshock (i.e., neglecting nonlinearity). These expected motions can then be compared to the actual recordings during the mainshock.

This analysis shows that the recorded strong-motion spectra are significantly overestimated if weak-motion amplifications are used. The null hypothesis, stating that the inferred differences between weak- and strong-motion amplifications are statistically insignificant, is rejected with 95% confidence in the frequency range from approximately 2.2 to 10 Hz. On average, the difference between weak- and strong-motion amplifications is a factor of 2. Nonlinear response at those soil stations for which the input peak acceleration exceeded 150 to 200 cm/sec^2 contributes most to this observed average difference. These findings suggest a significant nonlinear response at soil stations in the Los Angeles urban area during the Northridge mainshock. The effect is consistent with the increase in damping of shear waves at high levels of strain, which is well known from geotechnical studies of soil properties.

Introduction

In a companion article (Beresnev and Atkinson, 1998b), we applied the stochastic finite-fault radiation simulation technique (Beresnev and Atkinson, 1997, 1998a) to model strong-motion acceleration data from the *M* 6.7 1994 Northridge, California, mainshock. The method was calibrated against the data recorded at 28 free-field rock sites, at hypocentral distances of up to 94 km, in the Los Angeles urban area. The calibration essentially consists of determining the best value for the radiation-strength factor, which is the only free parameter used in the simulations; all other parameters are determined from known source geometry and regional physical properties. The calibrated method provides an accurate simulation of the spectral content of ground motions on average. The ratio of simulated to observed Fourier spectrum, averaged over all 28 sites, is indistinguishable from unity with 95% confidence in the frequency band from 0.1 to 12.5 Hz. The average ratio fluctuates about unity, with maximum excursions of no more than a factor of 1.35 at nearly all frequencies (Beresnev and Atkinson, 1998b, Fig. 5). There is also no systematic bias in individual-station prediction as a function of hypocentral distance, suggesting that the adopted attenuation model is unbiased over the distance range of the observations (Beresnev and Atkinson, 1998b, Fig. 6).

In this article, we apply the calibrated mainshock simulation model to the soil site recordings of the Northridge earthquake, obtained within the same distance range as the rock sites used in the calibration. The simulation of soil sites requires a knowledge of local amplification functions. Following the Northridge mainshock, a network of portable instruments was deployed to document aftershock activity (Hartzell *et al.,* 1996; Meremonte *et al.,* 1996). At 16 soil stations, temporary instruments were colocated with the permanent strong-motion accelerographs. The weak-motion amplification functions at all or some of the colocated sites, derived from the records of numerous aftershocks, have been independently determined by Hartzell *et al.* (1996), Bonilla *et al.* (1997), and Field *et al.* (1997).

We apply the calibrated model to simulate ground-motion recordings at these sixteen colocated soil sites. All parameters of the simulation are as given by Beresnev and Atkinson (1998b) (based on the slip distribution of Wald *et al.,* 1996), implemented using the FORTRAN code FINSIM (Beresnev and Atkinson, 1998a). Each simulated spectrum is amplified by the corresponding site-specific weak-motion amplification function. Our goal is not to provide an additional calibration of the method using soil-site data; this has been achieved from the recordings at 28 rock stations. The focus of this study is to check whether the use of weak-motion amplifications can reproduce the amplitudes recorded during the stronger levels of shaking during the mainshock, providing evidence regarding the linearity of soil response.

Site Geography and Strong-Motion Data

The locations of strong-motion stations used in this study are shown in Figure 1. The filled triangles indicate the 28 rock stations used for calibration (Beresnev and Atkinson, 1998b). The open triangles are the 16 colocated soil sites. Table 1 summarizes information regarding the soil sites. The classification as "soil" is based on Chang *et al.* (1996, Table 1) and the information on near-surface geology from the Southern California Earthquake Center (SCEC) strong-motion database. Station names are those adopted in the SCEC database.

The recorded data were obtained through the SCEC database. Recorded traces having a sampling interval of less than 0.01 sec were low-pass filtered and decimated to 0.01 sec. Other records were originally sampled at 0.01 or 0.02 sec; these were not resampled. In each case, the simulated traces have a sampling interval that matches that of the traces to which they are compared. A 12-sec cosine-tapered window of the observed shear wave was used to calculate its Fourier spectrum. The spectra of the two observed horizontal components were geometrically averaged.

Weak-Motion Amplification Functions

The local weak-motion responses at 16 colocated soil sites were determined from the aftershock recordings of the Northridge earthquake, by Hartzell *et al.* (1996), Bonilla *et al.* (1997), and Field *et al.* (1997). All authors use variations of the inversion procedure introduced by Andrews (1986). The method decomposes the recorded spectrum into the product of source, path, and site spectra and solves the resulting matrix equation to determine the site terms, assuming known source and path effects. The path effect is represented as a product of geometric-spreading and Q operators, derived empirically, and the source effect is determined from the spectrum recorded at a reference rock site, similarly corrected for path effect. The method is constrained by the assumption of a response of unity at a selected reference rock station. To alleviate possible bias associated with this assumption, a combination of rock sites can be selected as the reference condition. The inversion method described is equivalent to the spectral-ratio technique, where the ratios between soil and a reference rock site are corrected for path effect and averaged over all events available.

Figure 2 presents the amplification functions from all three investigations. We have only used responses determined on the basis of no less than five aftershocks; this explains the missing responses of Field *et al.* (1997) at site LSS (two aftershocks) and of Hartzell *et al.* (1996) at sites HST and SMI (one or two aftershocks). Hartzell *et al.* (1996) did not determine amplification at station LCN. In addition, Bonilla *et al.* (1997) estimate the responses at stations CPC, JFP, LF6, MPK, NWH, and SMI only. Field *et al.* (1997) use four reference rock sites (LWS, PCD, SCT, and SSA), marked as encircled filled triangles in Figure 1. Bonilla *et al.* (1997, Fig. 4 and Table 2) use a combination of three of the same stations (PCD, SCT, and SSA) and three other rock sites, for a total of six sites. Hartzell *et al.* (1996) determine all responses with respect to a single rock site at Encino reservoir, shown as the black square in Figure 1. Not all of the responses shown in Figure 2 are part of the original article by Hartzell *et al.* (1996); the amplifications for some of the stations were supplied by the authors in response to our request (S. Hartzell, written comm.).

There are two strong-motion instruments at station JFP: one in the administration building and one in the generator room (Table 1). The aftershock data have been collected at both locations. We combine both amplifications related to site JFP in Figure 2; however, Hartzell *et al.* (1996) determined the response for the generator room, and Bonilla *et al.* (1997) and Field *et al.* (1997) studied the administration building location. Its site-specific response will be used to simulate a particular strong-motion record at site JFP.

Figure 2 shows that the amplifications determined by Bonilla *et al.* (1997) and Field *et al.* (1997) are very similar, indicating that the inclusion of the three additional sites by Bonilla *et al.* (1997) did not affect the results in an appreciable way. The amplification functions of Hartzell *et al.* (1996) are generally close to these estimates, except for station VSP, where Hartzell *et al.* (1996) used 42 aftershock records and Field *et al.* (1997) used 5. For this reason, the amplification of Hartzell *et al.* (1996) at this site may be better constrained. The use of sets of amplification functions obtained from three independent studies is important in al-

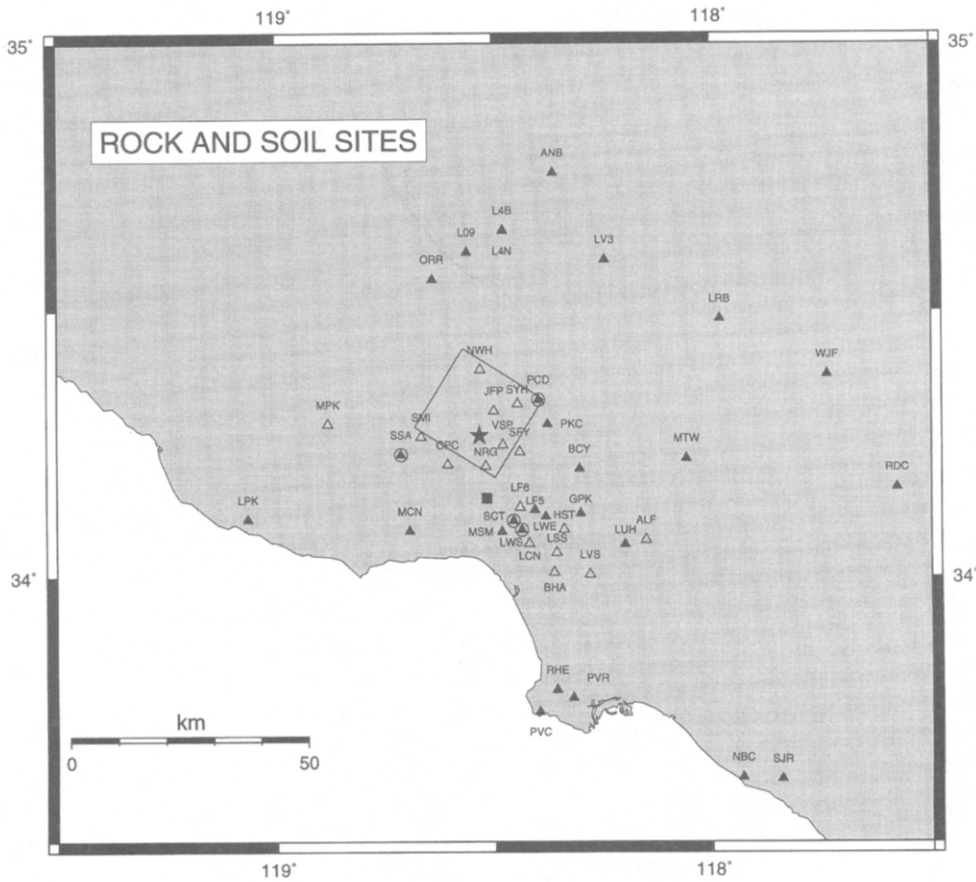


Figure 1. The rock and soil sites used in simulations. Filled triangles mark the 28 rock sites used for calibration of the method (Beresnev and Atkinson, 1998b). Open triangles are the 16 strong-motion stations with colocated instruments from the temporary aftershock observation network. Encircled filled triangles mark the rock stations (LWS, PCD, SCT, and SSA) used as reference sites in the estimation of weak-motion responses by Bonilla *et al.* (1997) and Field *et al.* (1997). The black square indicates the Encino reservoir rock site used as a reference by Hartzell *et al.* (1996). The surface projection of mainshock rupture plane is outlined by the box (Wald *et al.*, 1996). The thrust fault dips to the southwest at the angle of 40°, with the top edge at a depth of 5 km and the bottom edge at a depth of 21.1 km. The epicenter is marked with the star.

lowing us to verify whether the conclusions of our study depend on any specific selected set.

Comparison of Simulated and Observed Data

Figure 3 presents the recorded and simulated accelerograms and their Fourier spectra at soil sites. The 12-sec windows from two observed horizontal components are shown below the spectra. At station JFP, the records observed at the administration building are shown. The stochastic simulation provides a random horizontal component, which is shown as the bottom trace below the spectra. The aftershock site amplification functions derived by Field *et al.* (1997) were used. The simulation generally reproduces the shape, the duration, and the frequency content of the recorded accelerograms reasonably well, although the duration is underpredicted in some instances. This was also the case for rock sites (Beresnev and Atkinson, 1998b).

We notice from Figure 3 that many of the simulated spectral-amplitude levels exceed the observations. The peak ground acceleration is overpredicted in 10 out of 15 cases. We calculate the model error as the ratio of simulated to observed spectrum in the frequency band of 0.5 to 12.5 Hz, normalized by the average rock-station bias to account for the errors in predicting rock motions (Beresnev and Atkinson, 1998b, Fig. 5). The result is then averaged over all 15 sites. The mean error is presented in Figure 4, with the hatched band showing 95% confidence limits of the mean obtained from the *t* distribution. Figure 4 reveals a significant bias in simulation, in clear contrast to the simulation of rock sites, where the mean ratio of simulated to observed spectrum is not different from unity. The overprediction error, derived from the average curve in Figure 4, is approximately

Table 1
Soil Stations

Station Name	Latitude	Longitude	Location	Hypocentral Distance (km)	Predicted Base Peak Horizontal Acceleration (cm/sec^2)	Agency*
ALF	34.070	−118.150	Alhambra–Fremont School	43.6	75	CDMG
BHA	34.009	−118.361	Los Angeles–Baldwin Hills	33.6	89	CDMG
CPC	34.212	−118.605	USC #53	19.9	322	USC
HST	34.090	−118.338	Los Angeles–Hollywood Storage Bldg	29.8	151	SCEC
JFP	34.313	−118.498	Jensen Filter Plant–Administration Bldg	22.6	443	USGS
JFP	34.313	−118.498	Jensen Filter Plant–Generator Room	22.6	443	USGS
LCN	34.063	−118.418	Century City–Country Club North	27.5	136	CDMG
LF6	34.132	−118.439	USC #13	22.9	186	USC
LSS	34.046	−118.355	USC #91	31.4	105	USC
LVS	34.005	−118.279	USC #22	38.2	86	USC
MPK	34.288	−118.881	Moorpark	37.6	125	CDMG
NRG	34.209	−118.517	Northridge	19.1	280	USC
NWH	34.390	−118.530	Newhall–Los Angeles Country Fire Stn	27.7	382	CDMG
SFY	34.236	−118.439	Arleta–Nordhoff Ave Fire Stn	21.4	226	CDMG
SMI	34.264	−118.666	USC #55	23.0	396	USC
SYH	34.326	−118.444	Sylmar–County Hospital Parking Lot	24.7	452	CDMG
VSP	34.249	−118.478	Los Angeles–Sepulveda Hospital	20.4	403	USGS

*Name of agency that collected the data. CDMG: California Division of Mines and Geology; SCEC: Southern California Earthquake Center; USC: University of Southern California; USGS: United States Geological Survey.

a factor of 2 for frequencies above approximately 1.8 Hz. This causes the peak acceleration to be overpredicted in most cases as well.

We verify the significance of the average overprediction of soil-site motions inferred from Figure 4. The null hypothesis to be tested is that the average ratio of simulated to observed spectrum exceeded unity by random chance. A one-tailed t-test with 14 degrees of freedom is applicable here (e.g., Alder and Roessler, 1968, chap. 10). The dashed line in Figure 4 shows the 95% confidence limit for accepting the null hypothesis. At frequencies where the line lies at or below unity, the null hypothesis may be accepted; for frequencies where it is above unity, the null hypothesis may be rejected with 95% confidence. We conclude, at the 95% confidence level, that the strong motions at soil sites are overpredicted at frequencies between approximately 2.2 and 10 Hz, if weak-motion amplification functions are used. This means that the amplifications that actually occurred during the Northridge mainshock were significantly less than assumed at these frequencies, on average. The mean ratio of weak-motion to strong-motion amplification is approximately a factor of 2, as seen from Figure 4.

The question arises as to whether the selected reference rock sites might be a factor in the apparent bias seen on Figure 4. One could imagine a situation where the 4 sites selected by Field *et al.* (1997) might have unusually low site response of their own, leading to a substantial overestimation of the amplifications determined relative to them. This hypothesis seems unlikely, because the addition of 3 more reference stations by Bonilla *et al.* (1997) did not significantly change the estimated responses (Fig. 2). Nevertheless, we applied our simulation model to just the rock sites used as reference sites by Field *et al.* (1997), in order to determine if there is any simulation bias for these 4 stations. The result is shown in Figure 5. The 95% confidence limits of the mean ratio are wider than in the overall rock-station bias (Beresnev and Atkinson, 1998b, Fig. 5), because there are only 4 stations constraining the mean instead of 28. The ratio oscillates about unity and does not show any systematic error in the prediction. We conclude that the choice of these 4 reference sites is not the cause of the systematic simulation bias seen for soil sites in Figure 4.

Field *et al.* (1997) applied the spectral-ratio–based inversion technique to directly determine strong-motion amplifications at soil stations during the Northridge mainshock. The difference between weak- and strong-motion amplifications of a factor of 2 or smaller was found in the frequency band from approximately 1 to 6 Hz (Field *et al.*, 1997, Fig. 3). Our study, based on a finite-fault modeling approach and using a large number of rock sites for calibration, leads to generally consistent results.

It is interesting to determine which soil sites contributed most to the estimated average difference between weak- and strong-motion amplifications. The peak rock accelerations input at the base of each of the soil sites, as determined by our simulation procedure, are listed in Table 1. Figure 6 plots the ratio of weak- to strong-motion amplification at individual sites as a function of this input level of shaking intensity, at the frequency of 4 Hz, where the most significant reduction in amplification occurred (Fig. 4). The amplification ratio notably increases above the input acceleration value of approximately 150 to 200 cm/sec^2, a distinct indication of nonlinear ground behavior, although data scatter is significant. Ratios plotted for 3 to 9 Hz (not shown) have similar

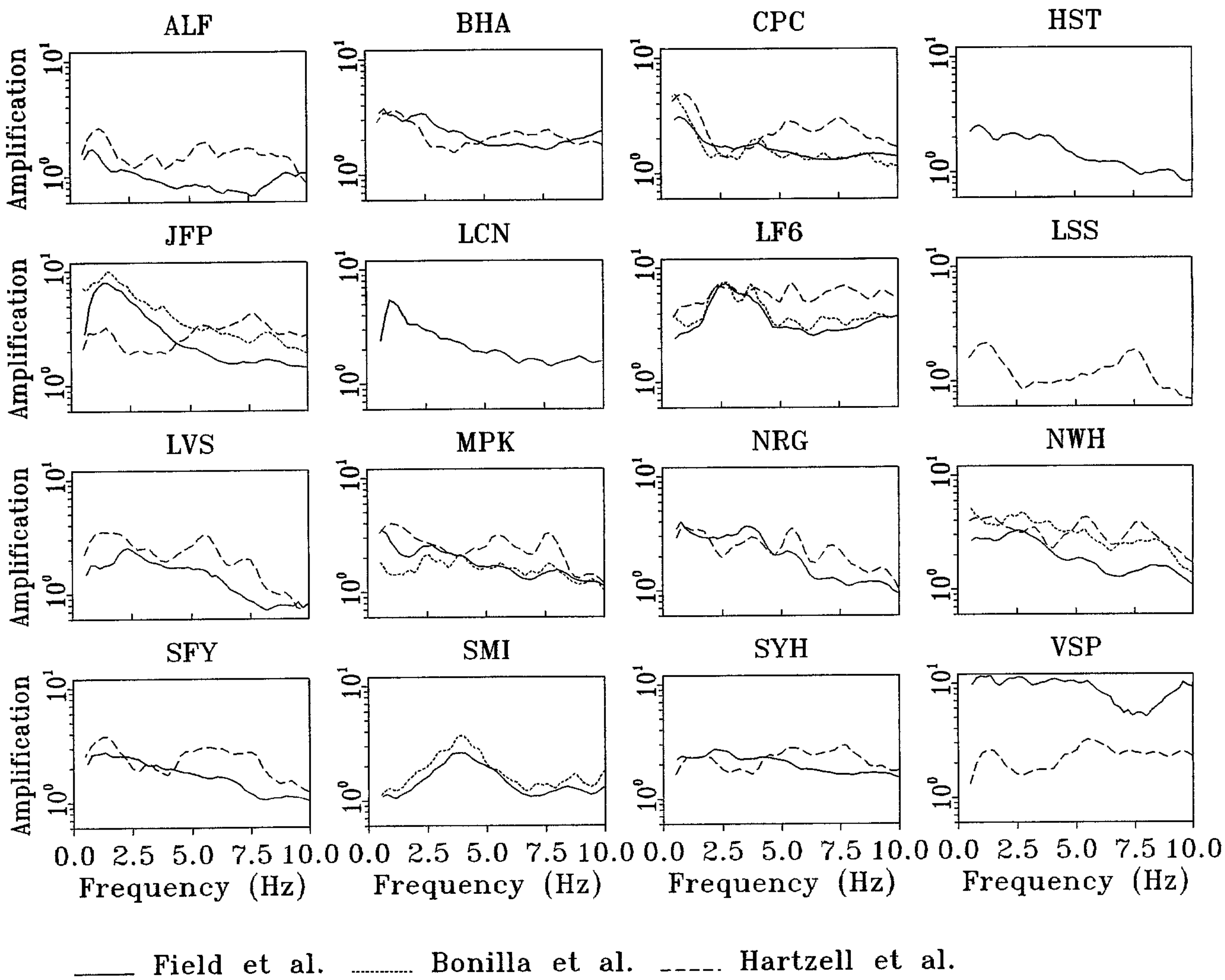


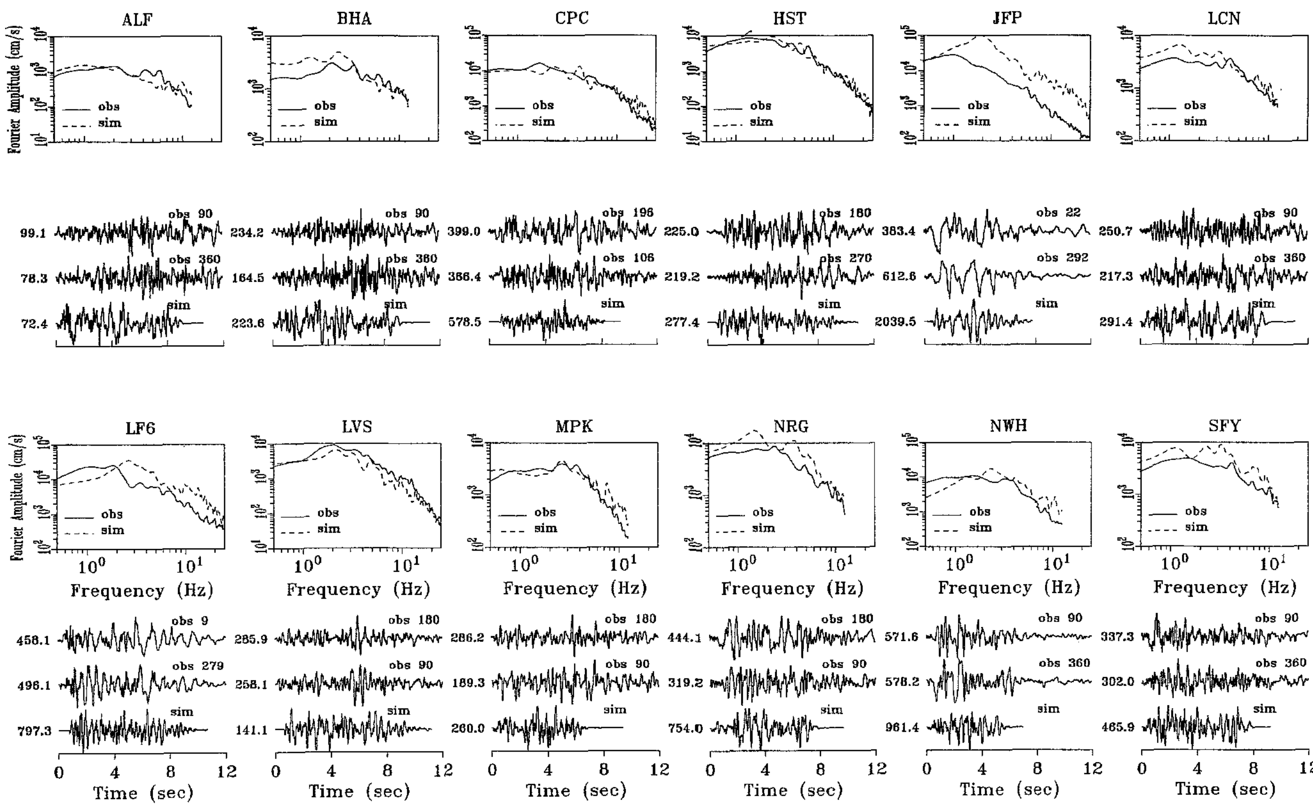
Figure 2. Soil amplification functions determined from three different inversions of Northridge aftershock data at 16 colocated sites. Only responses determined from no less than five aftershocks have been retained.

behavior. An apparent "threshold" of the onset of nonlinearity (150 to 200 cm/sec^2) is consistent with acceleration levels above which nonlinearity becomes important inferred from a number of independent observations (Beresnev and Wen, 1996a).

Abrahamson and Silva (1997) developed an empirical attenuation relation for response spectra on soil and rock sites, including peak acceleration on rock as one of the predictive variables and allowing for amplitude dependence of soil amplification. Defining amplification as the ratio of response-spectral values between soil and rock for a given distance and magnitude, then using equations (3) and (10) of Abrahamson and Silva (1997), we derive the following expression for the ratio of weak- to strong-motion amplification (a_w/a_s):

$$\frac{a_w}{a_s} = \left(\frac{\mathrm{PGA}_w + c_5}{\mathrm{PGA}_s + c_5}\right)^{a_{11}}, \qquad (1)$$

where PGA_w and PGA_s are the peak horizontal accelerations on rock (measured in g) in weak and strong motions, respectively, and c_5 and a_{11} are the empirical coefficients listed in Table 3 of Abrahamson and Silva (1997). At the period of 0.24 sec, closest to the frequency of 4 Hz considered previously, $c_5 = 0.03$ and $a_{11} = -0.223$. From a scrutiny of the database containing most of the aftershock records (http://www.scecdc.scec.org), the average peak acceleration at rock sites during the aftershocks can be taken as 5 cm/sec^2, or 0.005 g. Using these values in formula (1), we calculate the empirical curve showing the ratio of weak- to strong-motion amplifications as a function of PGA_s, which is plotted in Figure 6 as a dashed line. The Abrahamson–Silva line is reasonably consistent with our analysis, although some Northridge data show higher ratios of weak- to strong-motion amplification. Caution should be exercised in comparing the dashed line and the Northridge data in Figure 6, since the Abrahamson–Silva relation has been de-



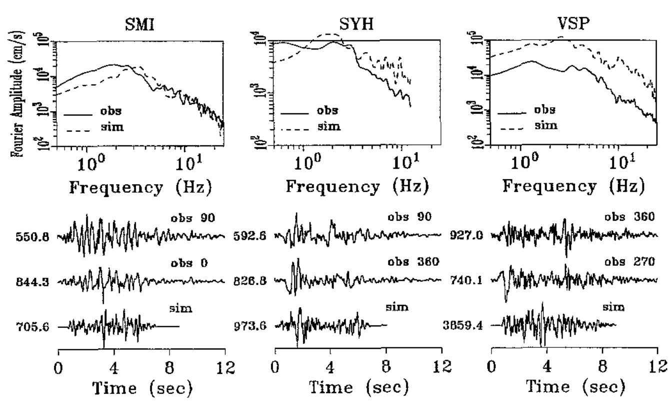


Figure 3. Recorded and simulated accelerograms and Fourier amplitude spectra at soil sites. Weak-motion amplification functions of Field *et al.* (1997) were used to generate simulated records. The observed and simulated spectra are shown by solid and dashed lines, respectively. The two upper traces below each spectrum are the observed horizontal accelerations, with the azimuth of the component indicated above the trace. The peak ground acceleration in cm/sec^2 is shown to the left of the traces.

veloped for response spectral values, while the ratios of Fourier spectral amplitudes are shown for the Northridge earthquake. In addition, the Abrahamson–Silva relation is valid for a generic soil site. In spite of these differences, both studies reflect a consistent trend of reduction in amplification as excitation level increases.

The simulations at soil sites were alternatively made using the weak-motion amplification functions estimated by Hartzell *et al.* (1996), who used a different reference station. The modeling bias, estimated in the same way as in Figure 4, is presented in Figure 7. The observed generator room data were used for site JFP. The interval of frequencies where the strong motions are overpredicted with 95% confidence are between 1 and 2 Hz, and 4 and 10 Hz, approximately. The existence of the lower interval (1 to 2 Hz) is only barely indicated by using the responses of Field *et al.* (1997) (Fig. 4) and should probably be taken with caution. The higher interval (4 to 10 Hz) is entirely consistent, being slightly narrower. The statistically significant difference in amplifications from the simulations using data of Hartzell *et al.* (1996) is larger, reaching a factor of 3 at 7.7 Hz. These quantitative differences are most likely attributed to the fact that only one reference site has been used by Hartzell *et al.* (1996). However, the overall conclusion about the signifi-

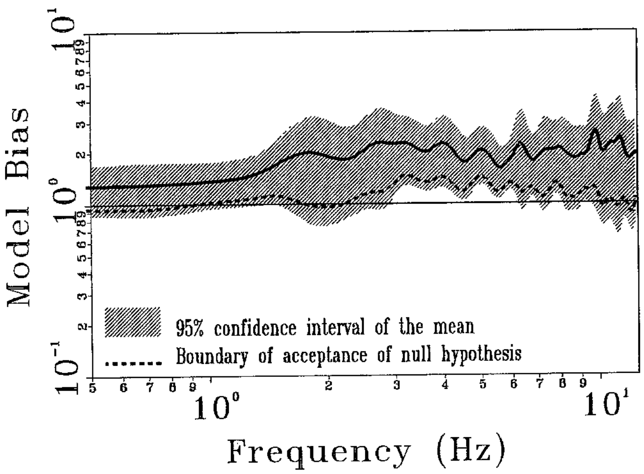


Figure 4. Model bias showing the ratio of simulated to observed spectrum, normalized by rock-station prediction bias and averaged over all 15 soil sites. The observed spectrum is calculated as the geometric average of the spectra of two horizontal components. The null hypothesis that the difference between simulated and observed spectra occurred by random chance is rejected with 95% confidence at frequencies between 2.2 and 10 Hz, approximately.

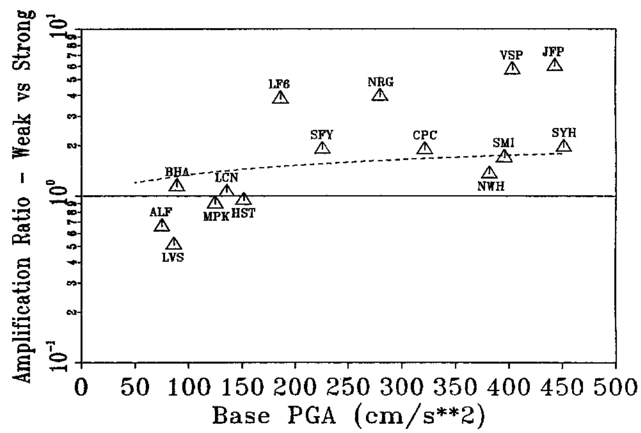


Figure 6. The ratio of weak- to strong-motion amplification at individual soil sites as a function of input peak acceleration at base of soil (triangles). Ratios are taken at 4 Hz. The dashed line shows the amplication ratio derived from an empirical attenuation relation of Abrahamson and Silva (1997), which allows for the dependence of soil response on base peak acceleration.

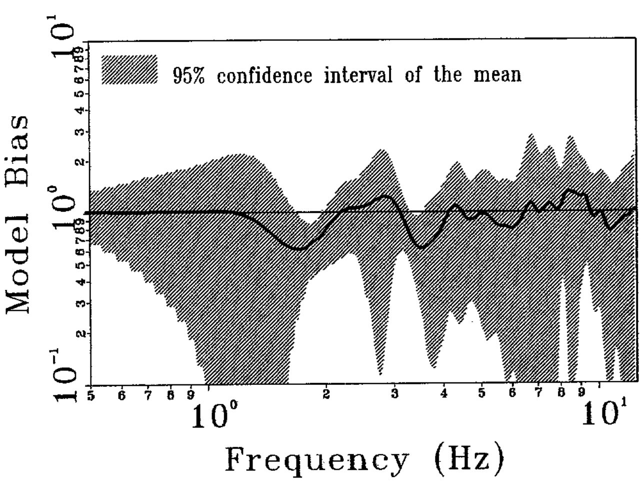


Figure 5. Model bias obtained from the method application to hard-rock sites LWS, PCD, SCT, and SSA, used as reference stations by Field *et al.* (1997). The mean ratio of simulated to observed spectrum is close to 1.

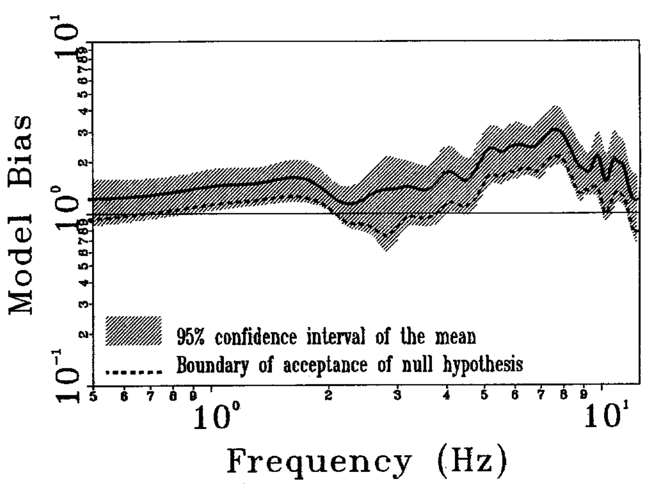


Figure 7. Model bias showing the ratio of simulated to observed spectrum, normalized by rock-station prediction bias and averaged over 13 soil sites. Weak-motion amplification functions of Hartzell *et al.* (1996) were used to generate simulated records. The null hypothesis that the difference between simulated and observed spectra occurred by random chance is rejected with 95% confidence at frequencies between 1 and 2 Hz, and 4 and 10 Hz, approximately.

cant overestimation of strong-motion amplification using weak-motion responses remains unchanged, regardless of which set of amplification functions is used.

Discussion and Conclusions

We simulated strong ground motions from the mainshock of the Northridge earthquake at 16 soil sites, for which estimates of weak-motion amplification are available. The method was first calibrated against the motions at 28 rock stations and is known to have a near-zero bias on average (Beresnev and Atkinson, 1998b, Fig. 5). From the simulation of rock-site recordings, it has been demonstrated that our method is unbiased over the distance range where the soil stations are located (Beresnev and Atkinson, 1998b, Fig. 6).

The same simulation procedure was applied to the soil sites, except that the simulated records were multiplied by site-specific amplification functions determined from inversion of aftershock data. Three different sets of responses available from the literature were used, as determined by three independent investigations. The simulated mainshock recordings significantly overpredict the observed motions at soil sites on average, regardless of which set of weak-motion amplifications is adopted. This provides strong evidence that weak-motion amplifications considerably overestimate the actual ground-motion amplification effects that occurred at soil sites during the Northridge mainshock.

Experimentally, soils are known to exhibit significant nonlinearity at the acceleration levels developed during the Northridge mainshock, ranging from 80 to 900 cm/sec^2 at the surface (Seed and Idriss, 1969; Hardin and Drnevich, 1972; Yu *et al.,* 1993). A reduction in soil amplification for strong motions relative to weak motions, caused by an increase in damping at high levels of strain, is a natural consequence. This effect was observed during the 1985 Michoacan, Mexico (Singh *et al.,* 1988), the 1989 Loma Prieta, California (Darragh and Shakal, 1991), and the 1995 Kobe (Hyogo-ken Nanbu), Japan, earthquakes (Aguirre and Irikura, 1997) and at miscellaneous locations throughout the world (Beresnev and Wen, 1996a). We attribute the significant overprediction of motions, revealed by the stochastic simulation at soil sites, to our use of weak-motion amplification functions, which do not correctly account for nonlinear site response. We conclude that the actual amplifications that occurred during the Northridge mainshock were, on average, significantly reduced by nonlinearity.

The method used to reveal soil nonlinearity in our study is similar to that used by Chin and Aki (1991), who reached similar conclusions for the epicentral area of the 1989 Loma Prieta, California, earthquake; these conclusions were the subject of some controversy (Chin and Aki, 1996; Wennerberg, 1996). There are two significant differences between our studies, though. First, unlike Chin and Aki (1991), we used site-specific amplification functions. Second, we derive our conclusions from the behavior of the entire ground-motion spectrum between 0.5 and 12.5 Hz, not just the peak accelerations.

Yu *et al.* (1993) predict, from numerical simulation of site response using a nonlinear constitutive law, that strong motions can actually be amplified over weak motions at the high-frequency end of the spectrum. This effect is due to higher-harmonic generation and may reveal itself at frequencies much higher that those addressed in our study (Yu *et al.,* 1993; Beresnev and Wen, 1996b). The effect is not seen at frequencies of up to 12.5 Hz for which we established the observed ratios of weak- to strong-motion amplification using Northridge data.

The nonlinear effect is clearly established not only from the average behavior of spectra, as seen from Figures 4 and 7, but also from the analysis of motions at individual sites. Figure 6 shows that the ratio of weak- to strong-motion amplification increases as a function of excitation level at the base of soil. This shows that the average effect observed in Figures 4 and 7 is attributable to soil sites with base peak accelerations exceeding 150 to 200 cm/sec^2. This threshold of the onset of nonlinearity coincides with estimates based on independent studies (Beresnev and Wen, 1996a). Our study further develops the conclusions of Harmsen (1997), who acknowledges that there has been significant nonlinear behavior for at least a few soil stations during the Northridge mainshock. Our conclusion is that the average nonlinear effect is significant and clearly observed. An estimate, based on Figure 4, is that there is a difference of about a factor of 2 in the amplification of weak versus strong motions, for frequencies between approximately 2.2 and 10 Hz. The application of weak-motion amplifications to estimate strong-motion response at soil stations would thus lead to a considerable overprediction of ground-motion amplitudes on average.

Acknowledgments

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