Quantification of Nonlinear Sediment Amplification During the 1994 Northridge Earthquake

USGS Award No.: 1434-97-GR03196

Edward H. Field
University of Southern California
Department of Earth Sciences
Los Angeles CA 90089-0740

Tel: 213-740-7088
Fax: 213-740-0011
E-mail: field@usc.edu

Program Elements: I, II

Key Words: strong ground motion, engineering seismology, site effects, and amplification

Investigations Undertaken:

It has been known since at least 1898 (Milne, 1898) that sediments can amplify earthquake ground motion relative to bedrock. For the weak motion of small earthquakes, sediment amplification is well understood in terms of linear elasticity (Aki, 1988). For the damaging ground motion produced by larger earthquakes, however, there has been a long-standing debate. Although recent earthquake studies have demonstrated nonlinear behavior under certain conditions (e.g. Beresnev & Wen, 1997), its significance for the type of stiff-soil sites found in the greater Los Angeles region remains an important question (as reflected in a recent seismic hazard assessment where some of the models applied assumed nonlinearity and some did not (Petersen et al., 1997)). This issue has been addressed with NEHRP funding.

By examining ground-motion for the Northridge earthquake and its aftershocks, we have found that sediment amplification was up to a factor of two less during the main shock implying a significant nonlinear response (Field et al., 1997). This interpretation has held up to an extensive set of tests of other possible explanations (Field et al., 1998a).

Specifically, we compiled data for all locations where both main shock and aftershock recordings were obtained. The 21 resultant sites are shown in Figure 1. Based on surface-geology, 15 of these sites are categorize as alluvium (Quaternary sediments), 2 as soft rock (Tertiary units), and 4 as relatively hard rock (Mesozoic basement). Also shown in Figure 1 are the epicentral locations of the 184 aftershocks used in this study, as well as the surface projection of the main-shock rupture distribution. To limit ourselves to a manageable quantity of data, only aftershocks with a magnitude between 3.0 and 5.6 were used.

To estimate site effects in the weak-motion aftershock recordings, the shear-wave Fourier amplitude spectrum observed at the i^{th} site for the j^{th} event, $O_{ij}(f)$, is represented as:

$$O_{ij}(f) = E_j(f)\, P_{ij}(f)\, S_i(f) \qquad (1)$$

where f is frequency, $E_j(f)$ is the source effect of the j^{th} event, $P_{ij}(f)$ is the path effect for the i^{th} station and j^{th} event, and $S_i(f)$ is the site response for the i^{th} site. The path effect is specified as:

$$P_{ij}(f) = r^{-1} \exp(-f\pi Ts/Q(f)) \qquad (2)$$

where r is the hypocentral distance measured from the aftershock location, T_S is the observed shear-wave travel time, and Q(f) is the quality factor representing attenuation.

The essence of the site-response estimation is as follows. After correcting the observations for the path effect by assuming some Q(f), the source effects are estimated from a site or average of sites, preferably on bedrock, assumed to have no significant site response. The response at the other sites is then estimated as the ratio between the path-effect-corrected observations and the estimated source effects. In actuality, the entire data set was solved simultaneously using a generalized inversion of equation (1) (e.g. Andrews, 1986). Of the many schemes that have been proposed, we follow that of Field & Jacob (1995) to ensure reliable uncertainty estimates.

The main-shock site response was estimated as for the aftershocks using equations (1) and (2). However, care must be taken in defining the hypocentral distance, r, because the spatial distribution of rupture (18 by 24 km, from Wald et al. (1996)) can be a significant fraction of the distance to each site. Care should also be taken in defining T_S because the rupture persists for several seconds. Therefore, some kind of average values of r and Ts must be used so that the effects of energy arriving from distances nearer and farther than r, as well as before and after T_S, are averaged out.

The estimates of both weak- and strong-motion site response obtained from equations (1) and (2) will be biased by any systematic difference between the actual path effects and that assumed in equation (2), or by any significant site response at the reference site(s). However, because our goal here is to identify any significant differences between the weak- and strong-motion response, and because the travel paths are similar between the main shock and aftershocks, these sources of bias will not influence the comparison as long as the same Q(f) and reference-site definition is applied in both cases.

One additional complication are finite-source effects, such as directivity (Archuleta & Hartzell, 1981), in the strong-motion observations. These result from the large spatial extent of the main shock rupture, where energy arriving from different locations on the fault plane may interfere constructively or destructively causing $E_j(f)$ to vary with site location. The potential influence of this was examined by computing finite source synthetics for the main shock and aftershocks. As discussed below, no evidence of a bias from finite source effects was found.

Results:

Figure 2 shows the weak- and strong-motion site-response estimates averaged over the 15 quaternary alluvium sites. These estimates were computed relative to the average of the four hard-rock sites, and we followed Hartzell et al. (1996) in assuming $Q(f) = 150\ f^{1/2}$. The weak-motion response implies an amplification factor of ~3.1 at 1 Hz, decreasing to factors of ~2.5 and ~1.4 at 3 and 10 Hz, respectively. The strong-motion amplification factors are systematically less, being ~1.9 at 1 Hz, ~1.3 at 3 Hz, and ~0.8 (deamplification) at 10 Hz. This lower amplification for the main shock implies nonlinearity.

The difference in weak- and strong-motion amplification factors was found to be significant over almost the entire frequency band at the 95-percent confidence level, and between 0.8 and 5.5 Hz at the 99-percent confidence level. One might ask whether the difference depends on any anomalous sites. In fact, at 3 Hz one must remove the 10 highest ratios (out of 15) from the average before the difference becomes insignificant at the 95-percent confidence level.

Many tests were conducted to evaluate the robustness of this observation. Details of those discussed below can be found in (Field et al., 1998a) As mentioned previously, any shortcomings of equation (2) in representing the path effects will be mapped onto the weak- and strong-motion estimates similarly, and should therefore not influence the comparison. Nevertheless, we applied several other Q models and found the results unchanged. Although it has been shown that bedrock sites can exhibit their own unique behavior (e.g. Cranswick, 1988), any significant site effect in our reference-site definition should influence both the weak- and strong-motion estimates similarly. Indeed, the significant difference exhibited in figure 2 does not depend on the inclusion of any particular rock site.

By far the most problematic source of bias could result from the large spatial extent of rupture during the main shock. For the strong motion estimates r and T_s were determined from the location and timing of maximum slip as determined by the inversion of Wald et al. (1996). This point, shown as a star in Figure 1, ruptured about 4.5 seconds after slip initiation at the hypocenter. However, we also computed r from all four corners of the rupture plane, and T_s from both the rupture initiation and termination 7 second later, and found the conclusions regarding the null hypothesis unchanged.

As an additional test of whether finite-source effects for the closest sites might be biasing the result, we performed the analysis using only the more distant LA Basin sites (LCN, HST, LSS, BHA, LVS, and ALF) relative to the rock site SCT. Although not as pronounced, the difference still persists. For example, at 3 Hz the difference is a factor of 1.6 and is significant at the 95-percent confidence level. That the difference is lower is consistent with the notion that nonlinearity at the more distant sites, where ground motion levels are lower, will be less.

As a final test of whether finite source effects might be masquerading as nonlinearity, we computed synthetic seismograms using the methodology and Northridge rupture model of Zeng & Anderson (1996)**.** Specifically, for the 21 sites considered here, and using the one-dimensional regional velocity model, we computed synthetic seismograms for the main shock and 9 relatively small events distributed equally over the main shock rupture plane. By conducting an analysis identical to that applied to the observed data, we have found no evidence for a significant bias due to finite source effects (Figure 3; see Field et al. (1998a) for more details).

Reports Published

Field et al. (1997, *Nature*), Field et al. (1998a, *JGR*), and a general state-of-knowledge paper on this topic was published by Field et al. (1998b, *SRL*).

Data Availability

All data used in this study are available upon request from: Edward H. Field, University of Southern California, Department of Earth Sciences, Los Angeles, CA 90089-0740 (Phone: (213) 740-7088; Fax: (213) 740-0011, Email: field@usc.edu).

References

Aki, K. 1988. Local site effects on strong ground motion. *Proc. of Earthq. Eng. and Soil Dynamics* II: 103-155.

Andrews, D. J. 1986. Objective determination of source parameters and similarity of earthquakes of different size. *Earthquake Source Mechanics*, Geophys. Monograph-37 6: 259-268.

Archuleta, R.J. & S.H. Hartzell 1981. Effects of fault finiteness on near-source ground motion. *Bull. Seism. Soc. Am*. 71: 939-957.

Bersenev, I. A. & K.-L. Wen 1997. Nonlinear soil response -- A reality? *Bull. Seism. Soc. Am.* 86: 1964-1978.

Cranswick, E. 1988. The information content of high-frequency seismograms and the near-surface geologic structure of "hard rock" recording sites. *Pure Appl. Geophys*. 128: 333-363.

Field, E. H. & K.H Jacob 1995. A comparison and test of various site response estimation techniques, including three that are not reference site dependent. *Bull. Seism. Soc. Am.* 85: 1127-1143.

Field, E.H., P.A. Johnson, Y. Zeng, & I. A. Beresnev 1997. Nonlinear ground-motion amplification by sediments during the 1994 Northridge earthquake, *Nature*, 390, 599-602

Field, E.H., Y. Zeng, P.A. Johnson, & I. A. Beresnev. 1998a. Nonlinear sediment response during the 1994 Northridge earthquake: observations and finite-source simulations, *J. Geophys. Res.*, In Press.

Field et al. (11 coauthors) 1998b. Nonlinear site response: Where We're At, *Seis. Res. Lett.*, 69, 230-234.

Hartzell, S, A. Leeds, A. Frankel, & J. Michael 1996. Site response for urban Los Angeles using aftershocks of the Northridge earthquake. *Bull. Seism. Soc. Am.* 86: S168-S192.

Milne, J. 1898. *Seismology*, 1st ed. : London, Kegan Paul, Trench, Truber.

Petersen, M.D., W.A. Bryant, C.H. Cramer, M.S. Reichle, & C.R. Real. 1997. Seismic ground-motion hazard mapping incorporating site effects for Los Angeles, Orange, and Ventura counties. *Bull. Seism. Soc. Am.* 87: 249-255.

Wald, D.J., T.H. Heaton, and K.W. Hudnut 1996. The slip history of the 1994 Northridge, California earthquake determined from strong-motion, teleseismic, GPS, and leveling data. *Bull. Seism. Soc. Am.* 86: S49-S70.

Zeng, Y. & Anderson, J.G. 1996. A composite source model of the 1994 Northridge earthquake using genetic algorithms. *Bull. Seism. Soc. Am.* 86: S71-S83.

Non-technical Summary

It has been known for over 100 years that sediments can amplify earthquake ground motion relative to bedrock. However, there has been a long-standing debate on whether amplification factors become lower (nonlinear response), or stay the same (linear response), as the level of shaking increases. By performing a careful statistical analysis of amplification factors between the Northridge earthquake (strong ground motion) and its aftershocks (relatively weak motion), we have document an approximate factor of two reduction in amplification during the main shock. This nonlinear-response interpretation stands up against other possible explanations, and brings into question some commonly made assumptions.

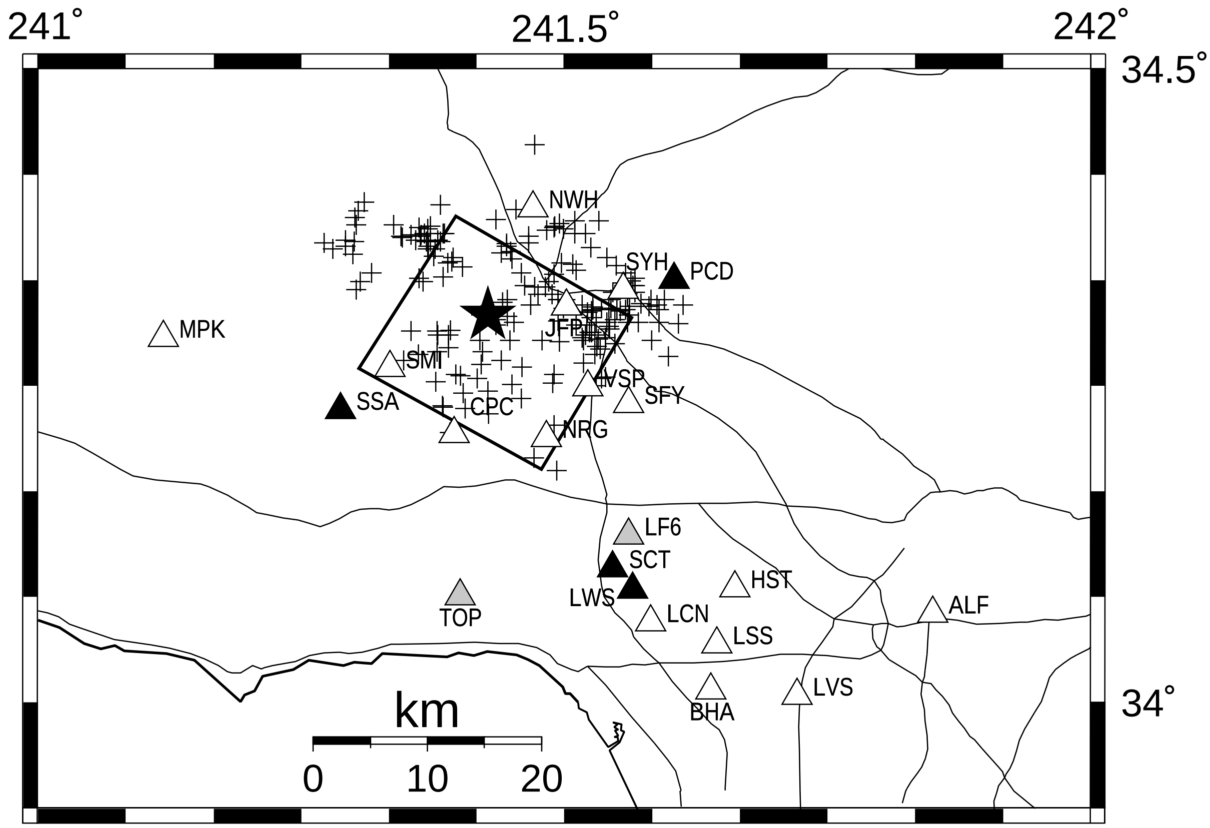

Figure 1. Relief map of the study region. The alluvium recording sites are shown as white triangles, the soft rock sites are shown as gray triangles, and the hard rock sites are shown as black triangles. Aftershocks epicenters are shown with crosses, and the main shock rupture distribution is outlined by the box (Wald et al., 1996). The fault plane dips to the southwest, with the top edge at a depth of 5 km and the bottom edge at a depth of 20.4 km. The location of maximum slip is marked with the solid star.

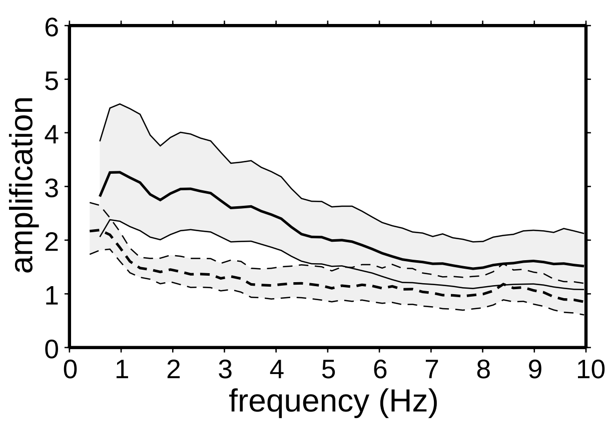

Figure 2. Mean and 95% confidence limits for the 15 alluvium site-amplification estimates. The solid lines represent the weak-motion results for the aftershocks, and the dashed lines represent the strong-motion results for the main shock.

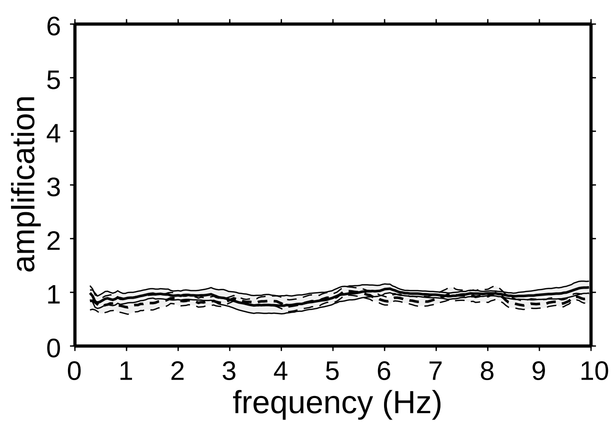

Figure 3. Same as figure 2, except that finite source and aftershock synthetics have been used. The agreement indicates that finite source effects are not producing the apparent nonlinearity.