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Paper No. 2030. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

SITE EFFECTS IN THE LOS ANGELES AREA DURING THE 1994 NORTHRIDGE EARTHQUAKE

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ABSTRACT

This paper describes empirical and modeling analyses of site effects in the Los Angeles in ground motion recordings of the Northridge earthquake and its aftershock sequence. In general, it is found that site response is not simply related to surficial geology, and there is evidence that deeper structure has an equally important influence on ground motion characteristics.

KEYWORDS

Northridge Earthquake; Site Response; Basin Response; Strong Ground Motion Simulation

INTRODUCTION

In order to identify site effects on the strong ground motions, we need to identify and separate out other effects that influence strong ground motions, including source and path effects. In the Northridge earthquake, the propagation of the rupture updip toward the north produced large variations in ground motion amplitudes, especially at periods longer than 0.5 second (Wald and Heaton, 1994; Somerville et al., 1996). The ground motions in the northern San Fernando Valley, the Santa Clarita Valley, and the intervening mountains were enhanced by this rupture directivity effect, which also produced larger motions in the fault normal direction (east northeast) than in the fault parallel direction (east southeast). Radiation pattern effects also caused the fault normal motions to be larger than the fault parallel motions in the central and southern San Fernando Valley, even though these regions were not subject to rupture directivity effects.

Another large source effect on the distribution of ground motion amplitudes is caused by the dipping orientation of the fault. The Northridge earthquake provided clear empirical evidence that peak ground accelerations on the hanging wall of thrust faults in the closest distance range of 10 to 20 km are as much as 50% larger than the average value for all site locations (Abrahamson and Somerville, 1996). Ground motion calculations using strong motion simulation methods show that the hanging wall effect is due mainly to the proximity of much of the fault to hanging wall sites. The hanging wall effect is most pronounced for periods shorter than about 0.5 seconds. At longer periods, ground motions are more strongly influenced by rupture directivity effects and less dependent on fault proximity.

Since both of these effects are due to source finiteness, their influence on the mainshock ground motions is expected to be larger than that on aftershock ground motions. If averaging of site response is done over a suite of aftershocks, it is likely that the effects of rupture directivity and differences between foot wall and hanging wall motions will be quite small. This indicates that aftershock data may provide valuable insight into site response.

EMPIRICAL MEASUREMENTS OF SITE RESPONSE FROM AFTERSHOCKS

Damage was concentrated in local zones which in most cases did not have strong motion recordings of the mainshock. Aftershock recorders were placed in many of these damage zones, and in most cases they recorded ground motions which indicated amplification when compared with reference stations at neighboring locations. The causes of local zones of damage in the Northridge earthquake are poorly understood. For example, at Sherman Oaks the zone of damage spans both alluvial and rock sites. In central Los Angeles, there is a positive correlation between damage and Holocene sediments, but in Santa Monica there is a negative correlation. This suggests that deeper lying structure (such as basin structure) may have as much influence on strong motion patterns as shallow structure.

Aftershocks of the Northridge earthquake were recorded by many organizations at many locations in the Los Angeles region. The results of these analyses will be published in early 1996 in a special volume of the Bulletin of the Seismological Society of America. Extensive analyses have been reported by Hartzell et al. (1996) and by Gao et al. (1996). Both of these studies found generally good correlation of high seismic response spectral values from aftershocks with localized areas of intense damage. However, broad trends in site response across the basins were not obvious. Hartzell et al. (1996) suggest that there may be lower site response near the southern margin of the San Fernando Valley caused by reflection of energy off the underface of north-dipping sedimentary layers. However, they conclude that the general rule appears to be randomness rather than order, characterized by pockets of large amplification, which include Tarzana and Sherman Oaks in the southern San Fernando Valley. They find that site response varies significantly within each surficial geologic unit. For example, they measured variations of a factor of two in site response over distances of 200m on the same surficial geologic unit. They found that at some alluvial basin sites, surface wave generation is a significant contributor to elevated site response at periods longer than about 0.5 second.

NON-LINEAR SOIL RESPONSE

Stiff soils in the near-source region of the Northridge earthquake did not deamplify ground motions in the manner predicted by most empirical attenuation relations and as prescribed in recent UBC and NEHRP code revisions. This is demonstrated in the comparison of peak ground accelerations and velocities for soil and rock sites derived from the Northridge mainshock data by Abrahamson and Somerville (1996), shown in Figure 1, and in the analyses of ratios of soil to rock motions by Borcherdt (1996). This suggests that deamplification due to nonlinear response of soils in the Northridge earthquake was offset by amplification due to impedance contrast effects. Information about seismic velocity structure and geotechnical data will be required at these recording sites in order to understand these effects. Irikura et al. (1995) measured microtremors with the objective of estimating velocity structure in Santa Monica and at several sites in the San Fernando Valley. Geotechnical borings sponsored by the NSF and Caltrans are planned at several of the sites that recorded large ground motions.

TOPOGRAPHIC AMPLIFICATION

Topographic amplification is suggested by intensity data in the Northridge earthquake, and by strong motion recordings at Pacoima Dam and Tarzana. However, the association between topographic amplification and very large high frequency ground motions recorded at the Pacomia Dam left abutment is complicated by the possibility of block movement as an alternative explanation. At Tarzana, extensive aftershock recordings showed that the large amplification of ground motions recorded during the mainshock was spatially very limited, and that there were significant differences in the response between the mainshock and the aftershocks. There appears to be a correlation between topography and amplification in the aftershock recordings, but the effects are very complex (Spudich et al., 1996), and the topography is not very steep. No model that explicitly relates the large recorded motions to topographic amplification has been proposed. Investigations of shallow velocity structure by Catchings and Lee (1995) found high values of Poisson's ratio in a low velocity zone beneath the mainshock recording site. These suggest that subsurface structure, as much as surface topography, may have contributed to the amplification observed at Tarzana.

INFERENCES ON SITE RESPONSE FROM MODELING AFTERSHOCK DATA

Song et al. (1995) found that aftershock waveforms recorded in and around the San Fernando basin are quite complex, even when the station is nearly on top of the source. The direct S phase at stations within 5 km are often distorted by precursory shoulders or peaks, thought to be S to P conversions at the bottom of the basin. Also, in some cases, the shear wave arrives on the radial component up to 0.5 seconds before it arrives on the tangential component. These observations suggest that complexities in the propagation path may have an influence on ground motion characteristics that is as important as that due to site effects.

Analysis of aftershock recordings by Gao et al. (1996) and Liu et al. (1995) indicates that the enhanced damage in Santa Monica may be explained by the focusing due to a lens structure at a depth of several km beneath the surface and having finite lateral extent. This was inferred from the observation of late-arriving S phases with large amplitudes which are localized in the zones of largest damage. The azimuths and angles of incidence of the seismic rays that give rise to the greatest focussing effects correspond to radiation that would have emerged from the lower part of the mainshock rupture surface. They hypothesize that the large ground motions in Santa Monica were highly dependent on the location of the Northridge earthquake, and that an earthquake of similar size located as little as one source dimension away would not be likely to repeat this pattern.

ANALYSIS OF BASIN RESPONSE IN MAINSHOCK STRONG MOTION RECORDS

The analysis of site response using aftershock recordings is generally limited to periods shorter than about 2 seconds due to the relatively narrow band response of the velocity transducers used to record the aftershocks. The aftershock recordings are thus not very useful for analyzing the effects of basin structure on ground motions. Basin structures affect surface ground motions at a larger scale than local site conditions, and these effects are most pronounced at periods longer than about 2 seconds.

Long-period ground motions recorded in the northwestern part of the Los Angeles basin, especially in Santa Monica and West Los Angeles, are dominated by large, late arriving pulses that are interpreted to be surface waves that became trapped in the southward thickening margin of the Los Angeles basin (top row of Figure 2). The lack of such waves in most recordings in the San Fernando Valley is due to the fact that the source was located beneath this basin, and body waves entered at at steep angles through its base instead of at shallow angles through its margins. The presence of these waves in the Los Angeles basin, and their absence in the San Fernando Valley, was inferred by calculating broadband simulated seismograms for the Northridge earthquake using a 1-D velocity model that ignores the basin structure, and comparing them with the recorded seismograms. The broadband simulation procedure is described by Somerville (1993). For these simulations, the source was represented by the rupture model of the Northridge earthquake developed by Wald and Heaton (1994).

We used the procedure of Abrahamson et al. (1990) to measure the goodness of fit of response spectral acceleration between the recorded and simulated ground motions. The goodness of fit is characterized by two parameters: the bias and the standard error. The bias measures the difference between the recorded and simulated motions averaged over all stations, and provides an indication of whether, on average, the simulation procedure is over-predicting, underpredicting, or even-predicting the recorded motions. The standard error measures the average difference between the simulated and recorded motions for a single observation, and provides an indication of the uncertainty involved in predicting a single value.

Averaged over 15 recordings in the San Fernando Valley, the simulation procedure has little significant bias (i.e. it neither over predicts nor under predicts the recorded ground motion on average) in the period range of 5.0 to 0.03 seconds, as shown on the left of Figure 3. The goodness of fit for three recordings in the northwestern Los Angeles Basin, shown in the center of Figure 3, indicates that the simulation procedure predicts these motions with no significant bias for frequencies larger than 0.5 Hz, but there is a significant underprediction of the recorded motions for frequencies lower than 0.5 Hz. Also, the durations of strong ground motions recorded at sites located in the northwestern part of the Los Angeles basin are significantly longer than those of the 1D simulations.

The enhanced long period levels and extended durations that are observed at these sites are caused by the trapping and reverberating of energy within the dipping sedimentary layers of the Los Angeles Basin, as shown by Graves (1995). In Figure 2, we show three different simulations of the recorded seismograms at four stations in the Los Angeles basin, shown at the top of Figure 2. The bottom row of Figure 2 shows simulations using a 1D model; the third row shows simulations using a 2D model of the Los Angeles basin, and the second row shows simulations using this model of the Los Angeles basin together with small shallow basins (microbasins). The role of these microbasins in amplifying and prolonging the duration of ground motion has been described by Saikia et al. (1993) in the Los Angeles basin and by Kawase and Aki (1989) in Mexico City. The microbasin model provides the best fit to the recorded seismograms in Figure 2. In Figure 4, we show the average response spectral ratios of the basin ground motions to bedrock ground motions for three recordings in the west Los Angeles basin. The response spectral ratios are for the simulated motions using a flat layered model; for the simulated motions incorporating the deep basin response; and for the simulated motions incorporating both deep basin and shallow microbasin response (Figures 3 and 4 of Graves, 1995). The simulation that incorporates both the deep basin and shallow microbasin response provides the best fit to the recorded data, and almost eliminates the underprediction of the data at periods longer than 2 seconds, as shown on the right of Figure 3.

CONCLUSIONS

In analyses of site response from aftershock studies, there is generally a good correlation of high seismic response spectral values from aftershocks with localized areas of intense damage. However, site response is not simply related to surficial geology, since it is found that site response varies significantly within each surficial geologic unit, and variations of a factor of two in site response are measured over distances of 200m on the same surficial geologic unit. This suggests that variations in ground motion levels may be due to deeper structure. Effects of deeper structure that have been proposed to explain amplification of ground motions at short periods include focusing caused by curvature of the interface between the bedrock and the overlying basin (both at the basin margin and within the basin) and by buried lens-shaped structure within basins. Effects that have been proposed to explain amplification at longer periods include the trapping of energy within basins and microbasins (small shallow basins within the larger basin structure). Stiff soils in the near-source region of the Northridge earthquake did not deamplify ground motions in the manner predicted by most empirical attenuation relations and as prescribed in recent UBC and NEHRP code revisions.

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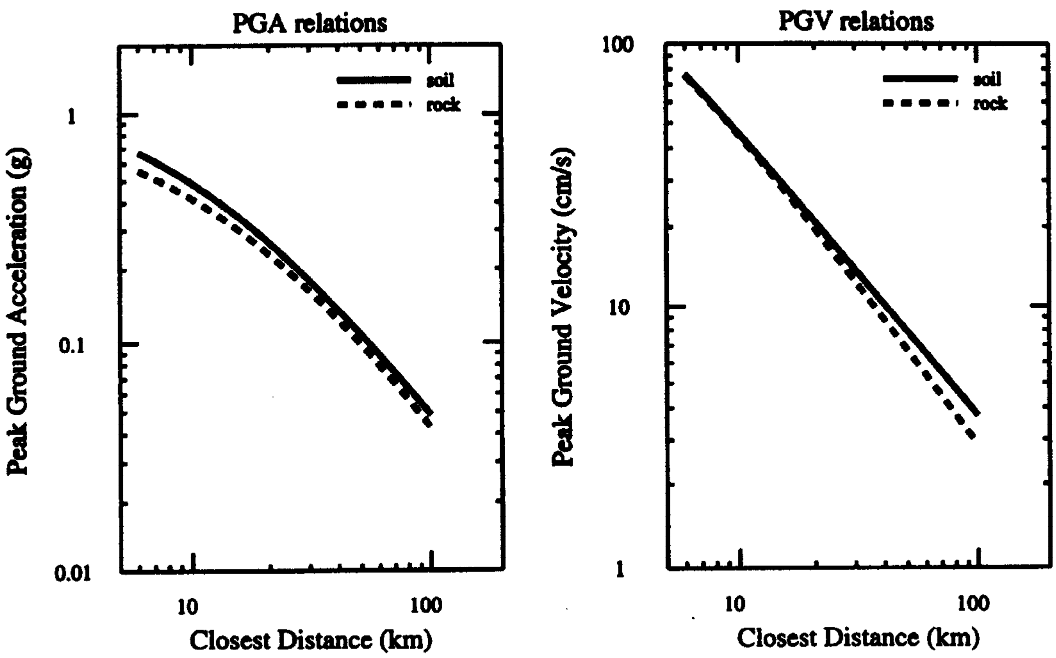

Figure 1. Attenuation of average horizontal peak acceleration and velocity recorded at soil and rock sites during the 1994 Northridge earthquake. Source: Abrahamson and Somerville, 1996.

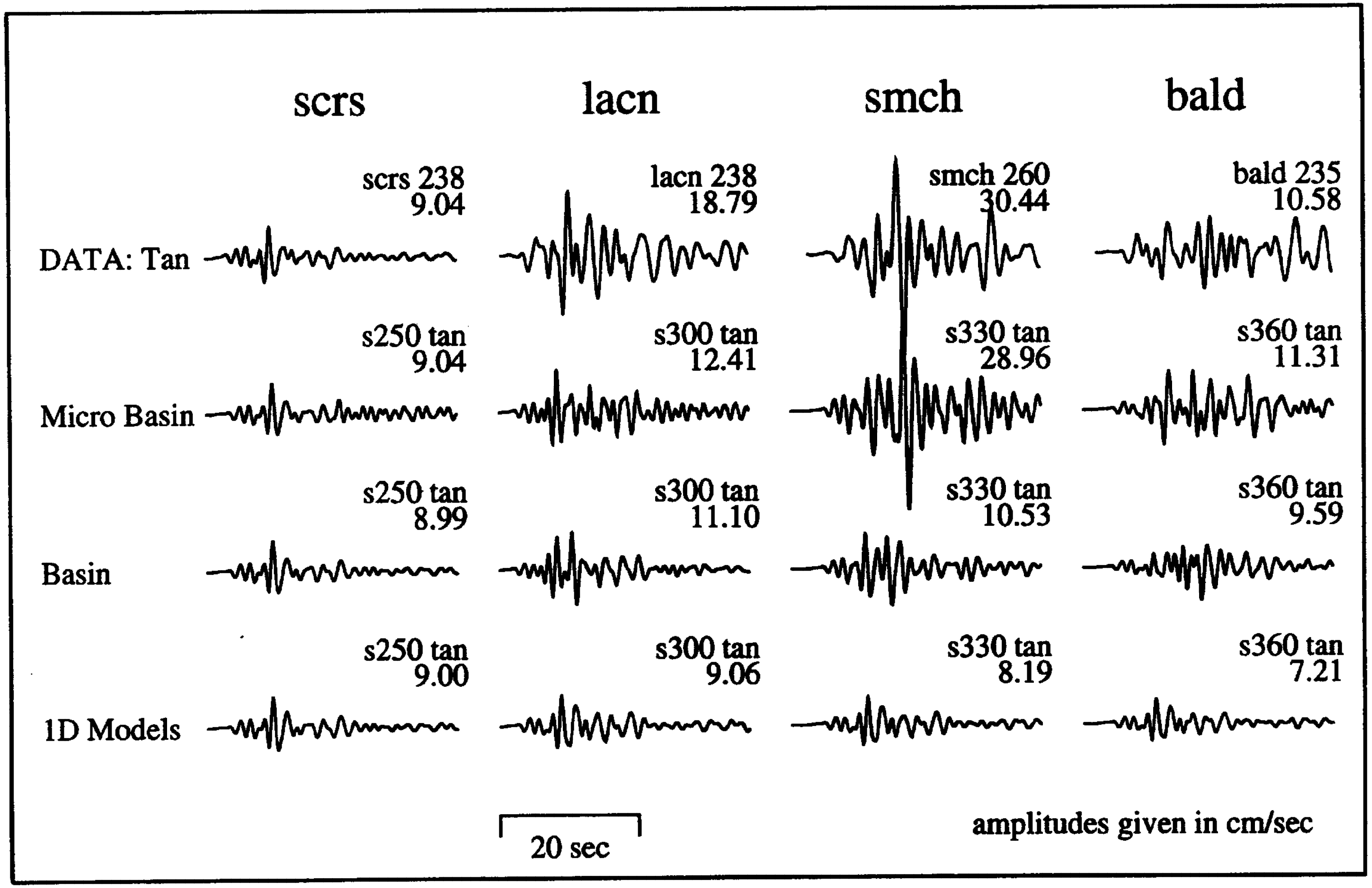

Figure 2. Comparison between the tangential component of velocity recorded during the Northridge earthquake at four sites located in west Los Angeles (top row) with the SH response simulated using the basin plus microbasin model (second row); the basin model (third row); and the 1D model (bottom row). Source: Graves, 1995.

Spectral Acceleration Goodness of Fit

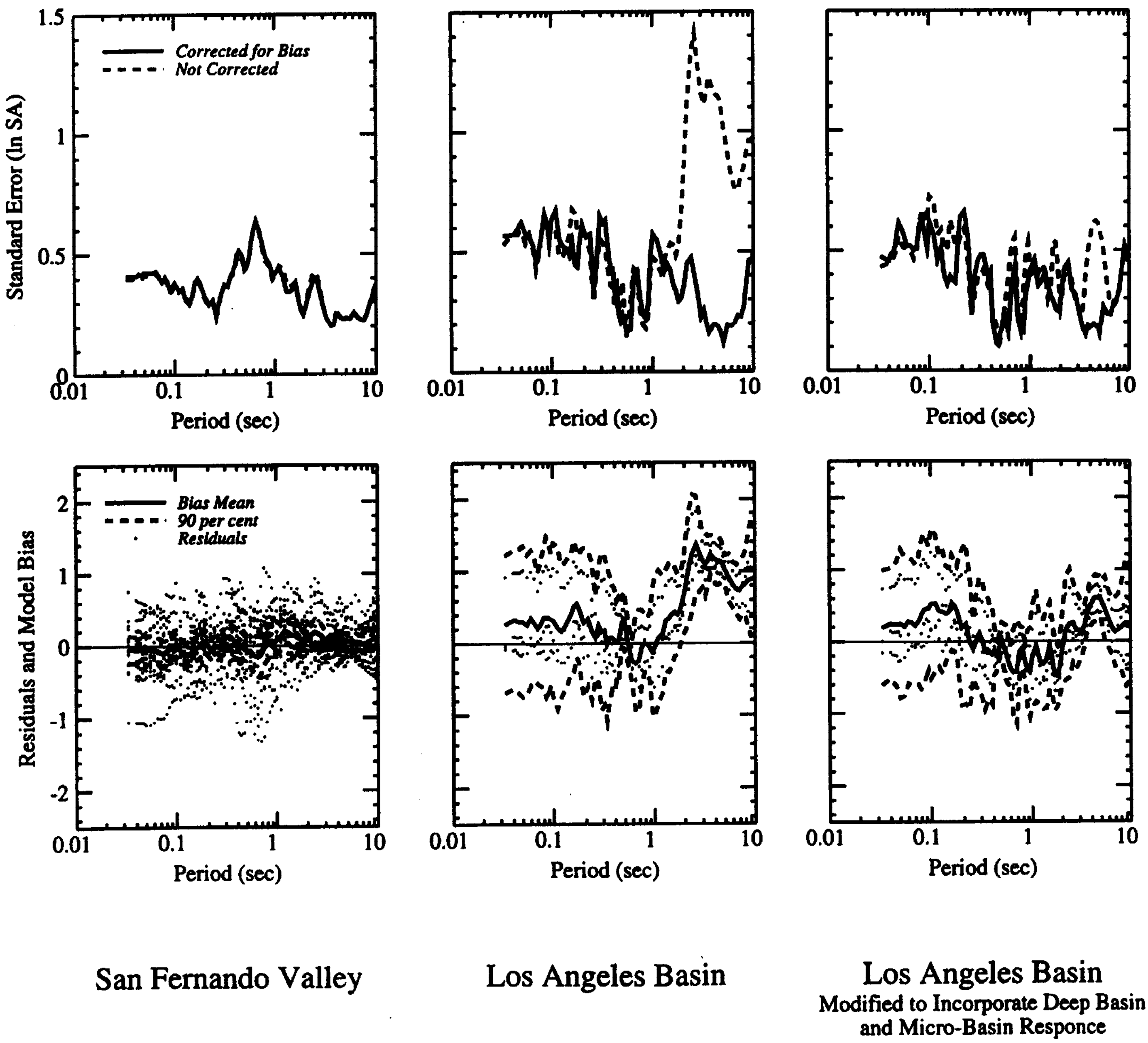

Figure 3. Performance of the 1-D broadband simulations in matching the 5% damped response spectra of the ground motions of the 1994 Northridge earthquake. The natural logarithm of model bias (positive bias indicates underprediction) is shown below, and the natural logarithm of standard error is shown above. Left: sites in the San Fernando Valley, 1D model; Center: sites in West Los Angeles, 1D model; Right: sites in West Los Angeles, modified using 2D model. Source: Somerville et al., 1996.

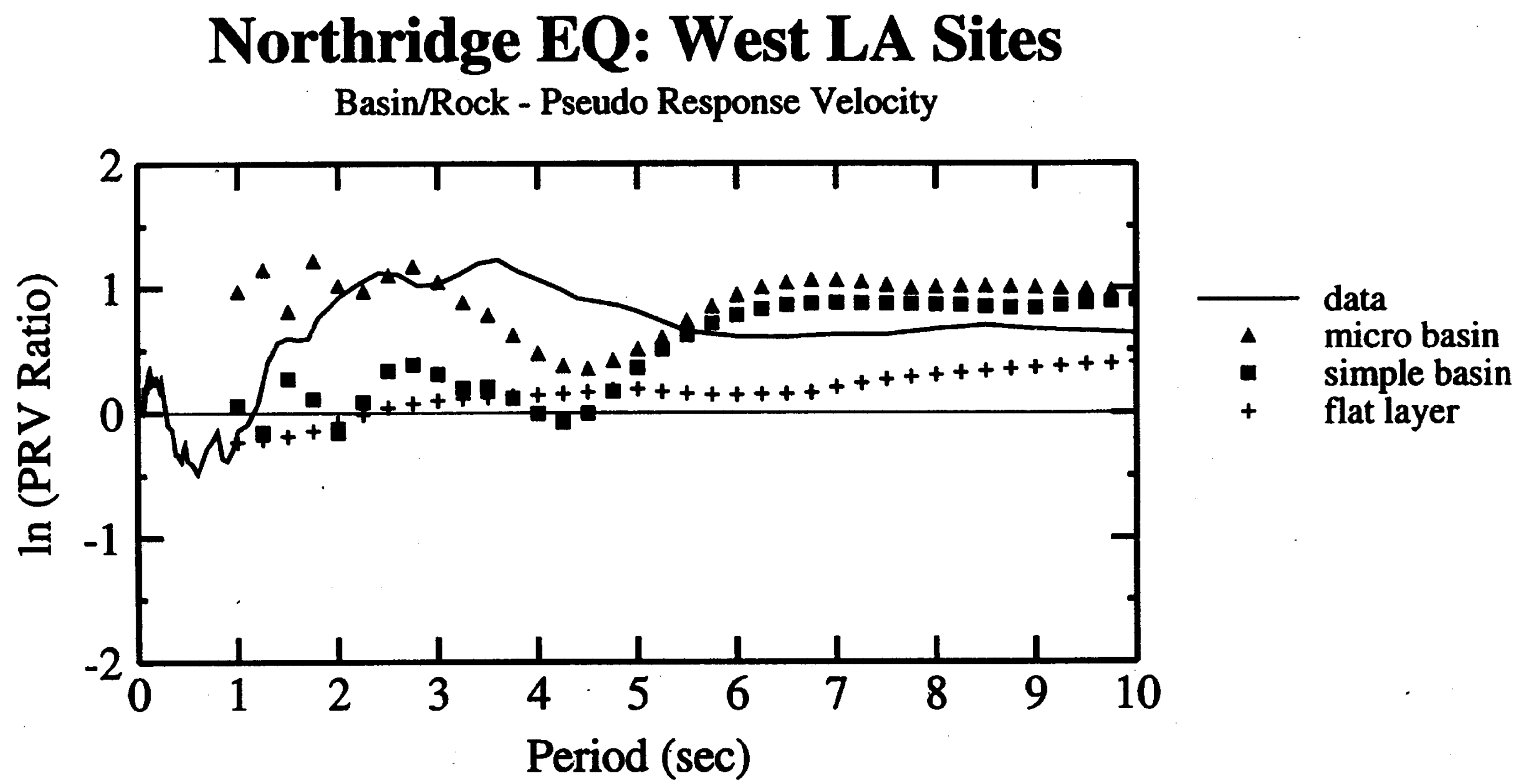

Figure 4. Response spectral ratios of basin ground motions with respect to a rock reference site for the recorded data; 1-D simulations; 1-D simulations modified for deep basin response; and 1-D simulations modified for both deep and shallow microbasin response. Source: Graves, 1995.