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ESTIMATION OF STRONG MOTION TIME HISTORIES EXPERIENCED BY STEEL BUILDINGS DURING THE 1994 NORTHRIDGE EARTHQUAKE

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ABSTRACT

This paper describes the generation of ground motion time histories at the sites of steel moment resisting frame buildings affected by the Northridge earthquake. These time histories were used by structural engineers to analyze the causes of brittle failures in the connections of steel moment resisting frame buildings in Phase 1 of the SAC Steel Project.

KEYWORDS

Northridge Earthquake; Steel Moment Frame Buildings; Strong Ground Motion Simulation; Basin Response

INTRODUCTION

Brittle fractures in steel connections during the Northridge earthquake have effectively invalidated current design methods for steel frame buildings. The SAC Joint Venture, a joint venture of the Structural Engineers' Association of California (SEAOC), Applied Technology Council (ATC), and California Universities for Research in Earthquake Engineering (CUREe), is conducting a coordinated three-year effort to develop cost-effective and reliable guidelines and standards of practice for design of new steel frame construction and the inspection, evaluation and rehabilitation of existing structures. In Phase 1 of the SAC Steel Program to Reduce Earthquake Hazards in Steel Moment Frame Structures, the performance of steel buildings during the Northridge earthquake has been documented and analyzed, the current state of knowledge and practice has been reviewed, and a preliminary test program has been conducted to assess proposed repair and design methods. Based on this and other information, Interim Guidelines for the Evaluation, Repair, Modification, and Design of Welded Steel Moment Frame Structures have been published (FEMA, 1995).

This paper describes the characterization of ground motions for use in a large number and variety of analyses by structural engineers in Phase 1 of the SAC Steel Project. The work had two specific objectives. The first objective, which is the focus of this paper, was to generate sets of ground motion time histories for particular sites of steel moment resisting frame buildings affected by the Northridge earthquake that were the subject of detailed analytical studies to understand the cause of the failures. The second objective was to develop ground motion contour maps to be used in conjunction with regional and individual building damage assessment efforts covering a larger number of buildings. The procedures used to generate ground motion time histories of the Northridge earthquake were validated by comparing simulated ground motions with the recorded ground motions of the Northridge earthquake, as well as with a large number of other events. These validated procedures formed the basis for generating ground motion time histories for the Northridge earthquake at the sites of buildings which did not have strong motion recordings.

At long periods, the strong ground motions of the Northridge earthquake were influenced by two important effects. Near the top of the surface projection of the fault in the northern part of the San Fernando Valley, very large long period ground motions were produced by rupture directivity effects (Wald and Heaton, 1994; Somerville et al., 1996a). Within the Los Angeles basin, large long period surface waves were generated by the interaction of incident body waves with the thickening margin of the deep Los Angeles basin (Graves, 1995; Somerville and Graves, 1993). Both of these effects were taken into account in the generation of broadband strong motion time histories at the sites of steel moment frame buildings.

BROADBAND STRONG MOTION TIME HISTORY SIMULATION PROCEDURE

The broadband ground motion simulation procedure is a hybrid procedure that computes the low frequency and high frequency ranges separately and then combines the two to produce a single time history. At frequencies below 1 Hz, it contains a theoretically rigorous representation of radiation pattern, rupture directivity and wave propagation effects, and reproduces recorded ground motion waveforms and amplitudes. The synthetic seismogram procedure that we use to generate the low frequency part of the broadband seismogram is described by Hartzell and Heaton (1983). It is implemented using an efficient frequency-wavenumber integration algorithm (Saikia, 1994) to compute Green's functions which are convolved with the slip function on the fault. At frequencies above 1 Hz, the procedure uses a theoretically rigorous representation of wave propagation effects which is combined with theoretically-based semi-empirical representations of stochastic processes including source radiation pattern and scattering in the path and site. The high frequency ground motion simulation procedure that we use is described by Wald et al. (1988) and Somerville (1993). It is implemented using a generalized ray method to calculate simplified Green's functions, which are convolved with empirical source functions derived from near-fault strong motion recordings of small earthquakes. The ground motion simulation model has no free parameters when used to model the recorded ground motions of a past earthquake.

The simulation procedure has been calibrated against the recorded strong motions from numerous earthquakes, including the 1978 Tabas; 1979 Imperial Valley (Wald et al., 1988); 1985 Michoacan, Mexico and Valparaiso, Chile (Somerville et al., 1991); 1987 Whittier Narrows; 1988 Saguenay, Quebec; 1989 Loma Prieta, and 1994 Northridge (Somerville et al., 1996b) earthquakes. Based on this validation experience, we have documented that the ground motion simulation procedure is applicable for magnitudes in the range of 5 to 8; distances from 0 to 200 km, and frequencies between 0.2 and 35 Hz.

This extensive validation of the simulation procedure leads us to expect it to produce accurate estimates of ground motions for any given rupture scenario. Before the 1994 Northridge earthquake occurred, we simulated the strong ground motions for a magnitude 7 earthquake on the Elysian Park blind thrust beneath downtown Los Angeles. No good examples of strong motion recordings of such a blind thrust event existed in the strong motion data base until the occurrence of the Northridge earthquake. The close agreement between our pre-Northridge estimates for the Elysian Park scenario event (Saikia, 1993) and the ground motions recorded during the Northridge earthquake, shown in Figure 1, is a successful blind test validation of the simulation procedure.

SIMULATION OF BROADBAND TIME HISTORIES OF THE NORTHRIDGE EARTHQUAKE

The broadband simulation procedure was used to generate strong motion time histories of the 1994 Northridge earthquake for use by structural engineers in analyzing the causes of brittle failures in the moment frame connections of steel buildings as part of the SAC Steel Project (Somerville et al., 1995). These time histories were needed for the analysis of buildings for which there are no strong motion recordings of the Northridge earthquake. As a preliminary step, we checked the performance of our broadband simulation procedure against the recorded strong motions of the Northridge earthquake.

In general, the simulated ground motion time histories show a fairly close resemblance to the waveforms of the recorded motions at low frequencies. This is as expected since the rupture model was derived from the lowpass filtered strong motion waveforms. In Figure 2, we compare the recorded three component time histories at Arleta (top row) with those simulated using empirical source functions derived from the Whittier Narrows aftershock (center row) and the Imperial Valley aftershock (bottom row of each panel). The recorded and simulated displacement waveforms are quite similar, especially on the north component. There is also considerable resemblance between the recorded and simulated velocity waveforms, especially in the lower frequency features. At high frequencies, there is little resemblance in waveform between the recorded and simulated motions, as seen in comparing the recorded and simulated time histories, but there is resemblance in the duration of the strong motion.

We use 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. At a given station and for a particular period, the standard error is about a factor of 1.4 on average over the period range of 5.0 to 0.03 seconds, as shown in Figure 4. This means that, due to the limitations of the simulation procedure, which at short periods may relate to the inherently stochastic nature of strong ground motion, our simulated motions at a given site for a given period have an uncertainty whose standard error is on average about a factor of 1.4.

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, and 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).

To generate realistic time histories of the Northridge earthquake in the western Los Angeles basin, we used a simple 2D model of the Los Angeles basin to generate a site transfer function for modifying time histories calculated using a flat layered geology model (Figure 4 of Graves, 1995). Examples of these time histories are shown at the top of Figure 4. Those on the left were calculated using the 1D model, and those on the right are modifications that include the basin response in an approximate way using the site transfer function. The effect of the basin response is to increase the duration of the long period ground motions by about a factor of two and increase the peak velocity by about fifty percent.

At the bottom of 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 (Saikia et al., 1993) provides the best fit to the recorded data. The improvement in goodness of fit to the response spectra of the recorded data over that of the flat layered model is shown on the right side of Figure 3.

CONCLUSIONS

Strong motion simulation procedures were effectively used to simulate broadband time histories of ground motions experienced at the sites of steel buildings during the 1994 Northridge earthquake, based on a rupture model of the earthquake developed by Wald and Heaton (1994). In the San Fernando Valley, the strongest ground motion effects at long periods are due to rupture directivity toward the north, which were effectively modeled by our procedure. In the Los Angeles Basin, the strongest effects on long period ground motions were due to the generation of surface waves by body waves becoming trapped within the Los Angeles Basin. The adequate modeling of these effects required the use of a two dimensional seismic velocity model of the basin structure.

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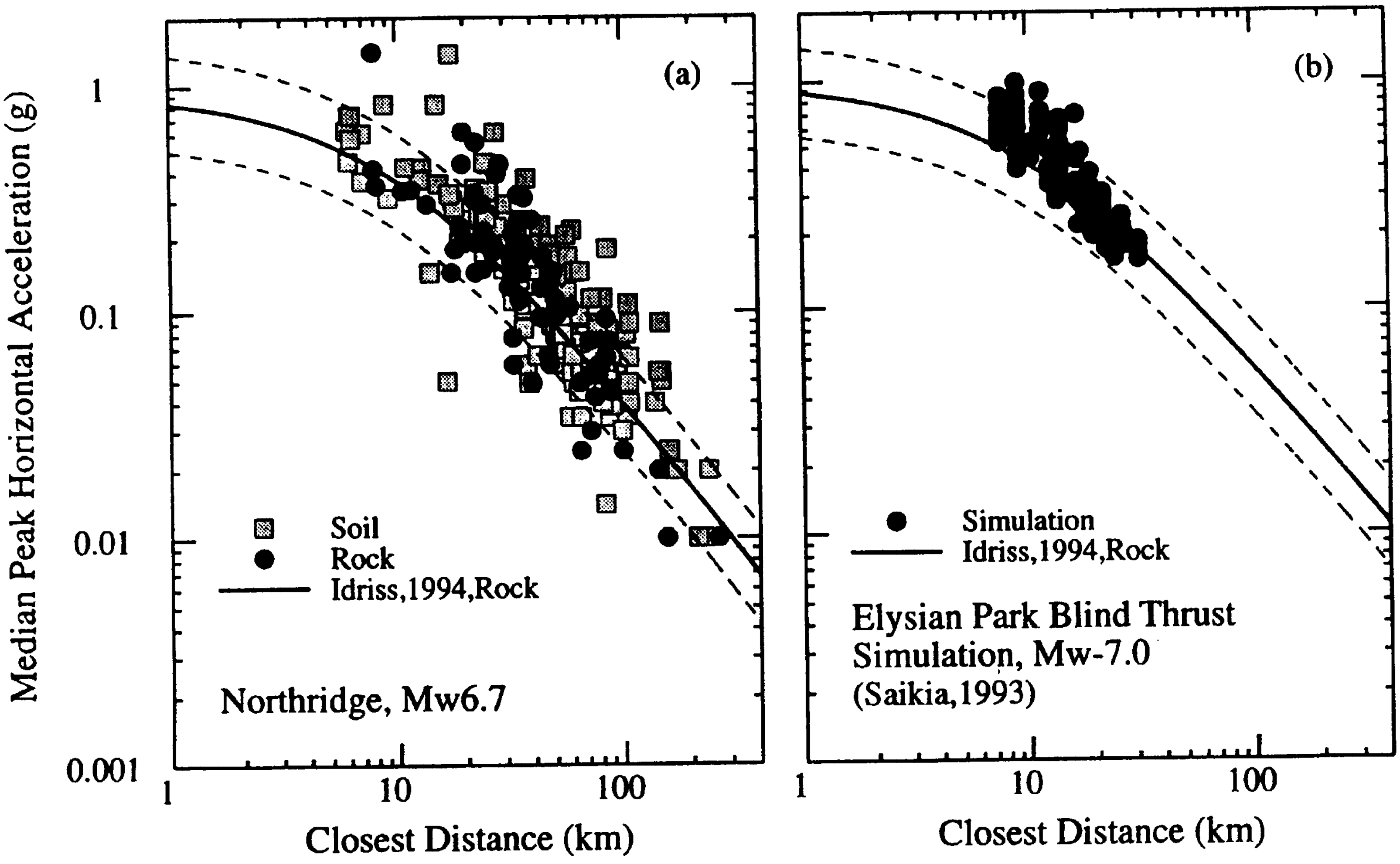

Figure 1. (a) Comparison of recorded peak accelerations from the Northridge earthquake with the attenuation relation of Idriss (1991) for thrust earthquakes on rock and stiff soil sites. (b) Comparison of simulated peak accelerations for a M_W 7 earthquake on the Elysian Park blind thrust (Saikia, 1993) with the relation of Idriss (1991).

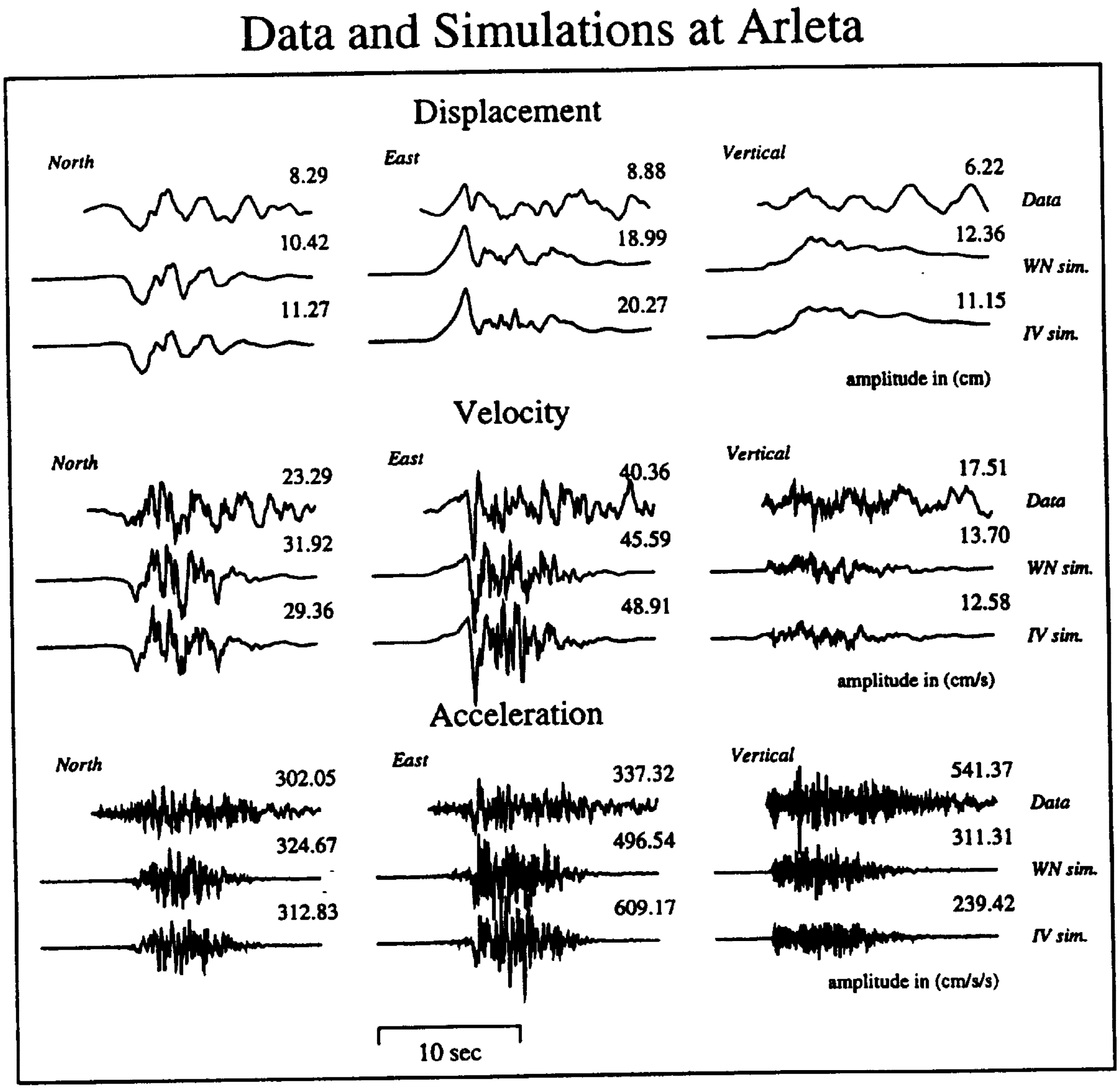

Figure 2. Comparison of recorded (top row) and simulated (middle and bottom rows) displacement, velocity and acceleration time histories at Arleta from the 1994 Northridge earthquake, plotted on a common scale, with peak value given in the top left corner.

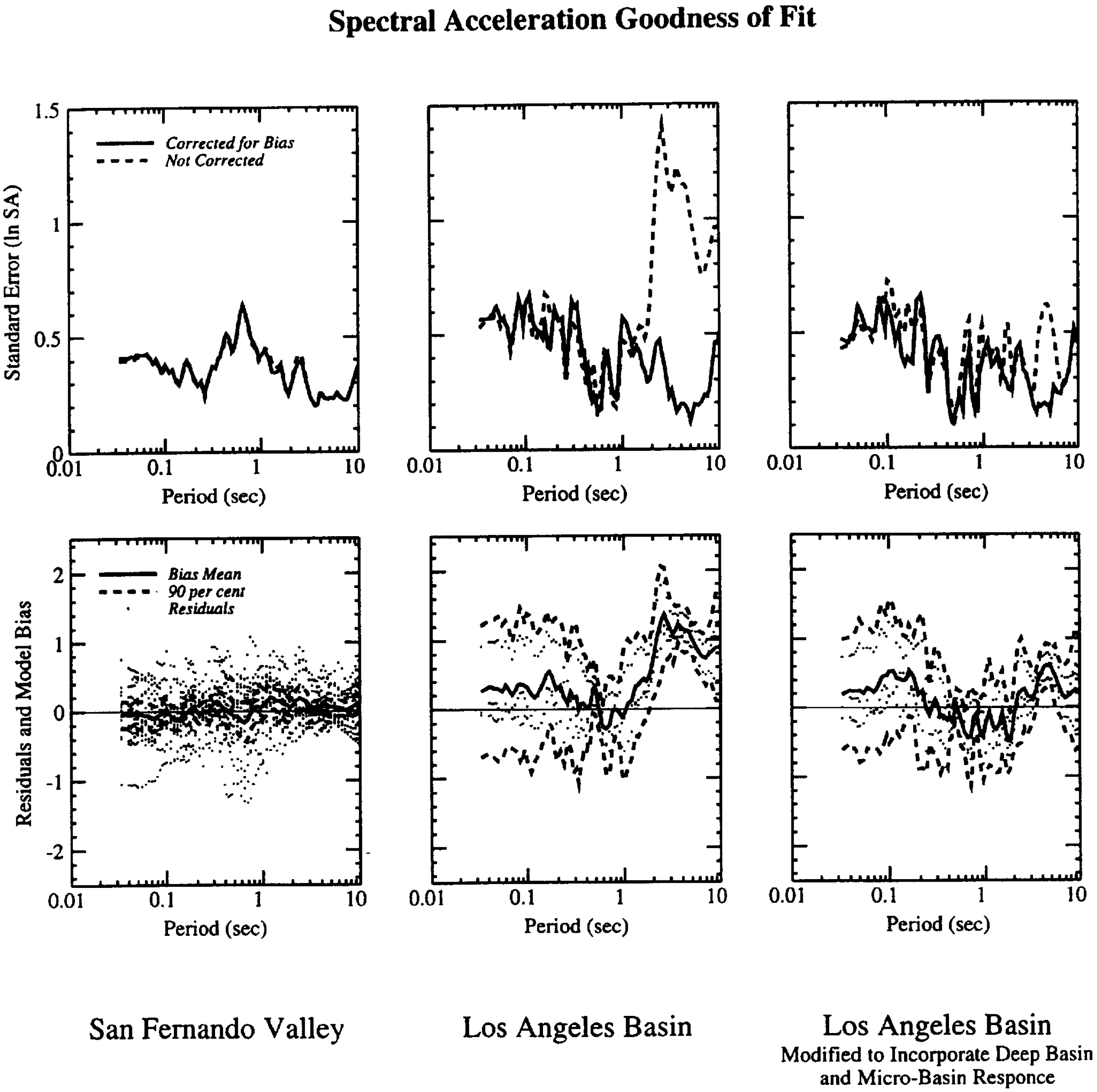

Figure 3. Performance of the 1-D broadband simulations in matching the 5% damped response spectra of the ground motions of the 1994 Northridge earthquake. The natural logarithm of model bias (positive bias indicates underprediction) is shown below, and the natural logarithm of standard error is shown 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.

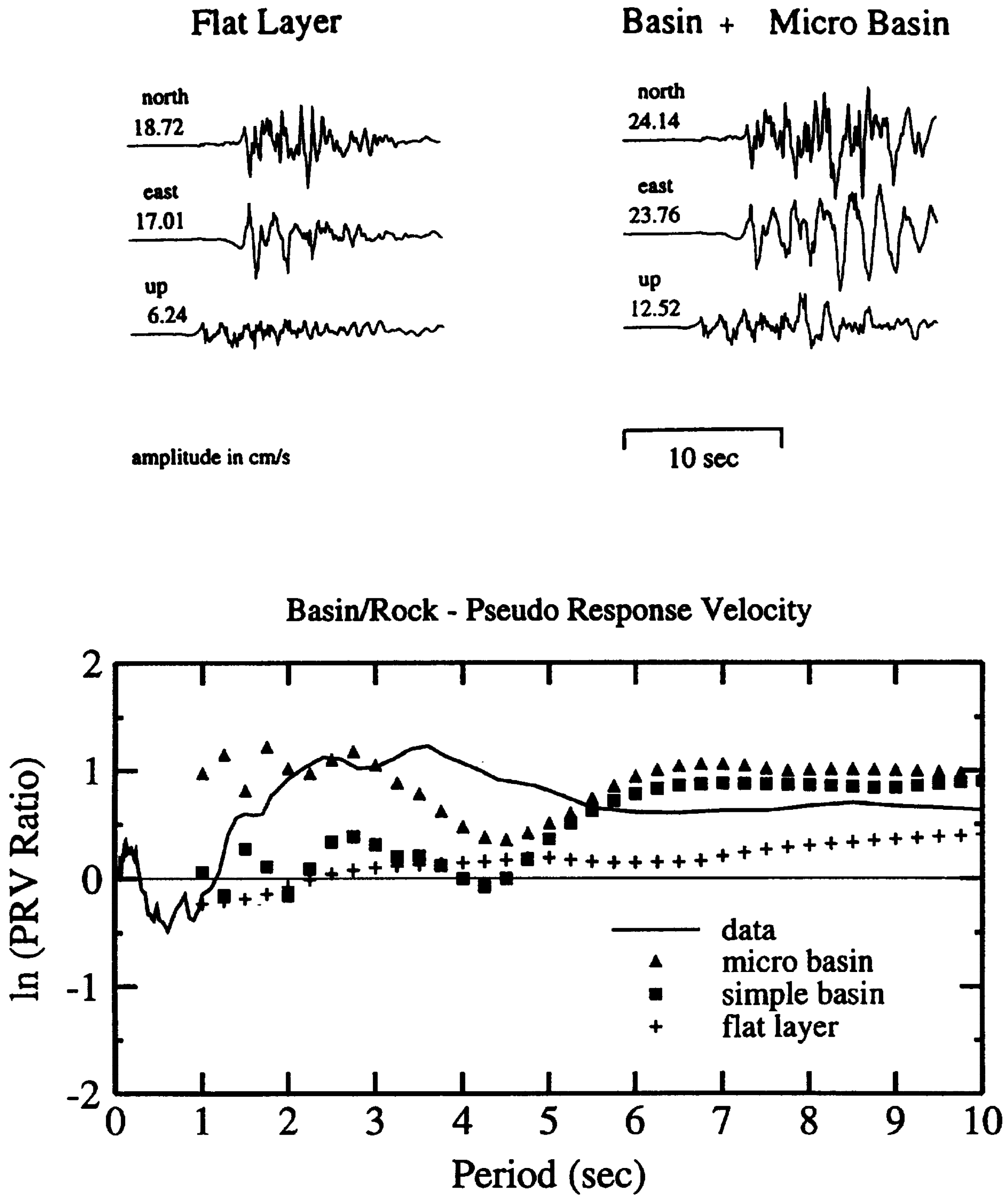

Figure 4. Top: Comparison of simulated velocity time histories in West Los Angeles for the 1994 Northridge earthquake calculated for a 1D model (left); and modified to account for basin effects using a transfer function calculated using a 2D model (right). Bottom: Response spectral ratios of basin ground 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.