Appendix B
Synthesizing a Suite of Simulated Recorded Motions

B.1 Introduction

a. Using existing time-histories recorded under conditions representative of the design earthquake is an appealing and logical approach to obtain design time-histories. However, there may not always be an adequate suite of recorded motions that are representative of the design earthquake conditions in terms of such factors as the tectonic environment, earthquake magnitude and other characteristics, earthquake source-to-site distance, and subsurface conditions. Despite the significant increase in the number of recordings during the past 25 years, data gaps remain. For example, there is no record representing the near-source region of a large ($\boldsymbol{M_w}$. 8) strike-slip earthquake that has a high probability to occur on the San Andreas Fault system in this century. Similarly, in the northwestern United States and Alaska, where a very large subduction zone earthquake ($\boldsymbol{M_w} \sim 9$) is possible, recordings from this type of megathrust earthquake are also unavailable. In the central and eastern United States, there are only a few acceleration time-histories from moderate to large earthquakes at close distances.

b. An alternative or supplement to using recorded time-histories is to develop synthetic time-histories based on the theoretical models of earthquake source processes and seismic wave propagation. These models can be used to produce more realistic time-histories than those produced by methods that do not contain seismological controls. The synthetic motions may be computed for three orthogonal components of acceleration at a site.

c. There is a large diversity of approaches to ground motion simulations. These approaches reflect differences in motivations, degree of simplification, and objectives behind individual approaches. Nevertheless, each method accommodates the common aspects that seismic waves are generated by a ruptured fault of finite dimensions and are propagated through the crust to the site at the surface of the earth. In this appendix, these basic aspects of ground motion simulation are discussed, and information relevant to the generation of time-histories for use in engineering design is presented. The objective is to provide an understanding of the basic ideas behind time-history simulations. Validating the simulation procedures is also discussed in this appendix.

B.2 Ground Motion Simulation Model

The computational model for synthetic seismograms consists of three driving processes: the seismic source process, the process of seismic wave propagation from the source region to the design site, and the process of shallow site response. The issue of site response is discussed in Section 5.6; this appendix focuses on simulations for rock site conditions not including local site response effects. It should be noted that randomness is often introduced, either in the source process or in the wave propagation, to model the complexity of observed seismograms.

a. Earthquake source process.

(1) Reid's elastic-rebound theory (Reid 1911) is the foundation of the modern earthquake source model now being widely adapted by the seismological community. Reid's hypothesis explains the origin of earthquakes by a fracture in prestrained crust. In his elastic-rebound theory, strains are accumulated in the crustal rock surrounding the fault. The rock finally reaches a failure point. Rupture then takes place, and the strained rock rebounds on each side of the fault (fault slips) under its own stresses until the strain is largely or completely released. The abrupt fault slip is the cause of seismic waves and hence of macroseismic shaking.

An important notion conveyed by Reid's elastic-rebound theory is that fault rupture takes place at first in a small area and quickly grows into a larger area at a rate not greater than the compressional wave velocity of the rock. Furthermore, a point on the fault starts to slip only when the moving rupture front arrives at that point, and it takes a finite amount of time (rise time) for that point to complete the slip. The propagating rupture front and finite rise time are essential to the explanation of directivity, near-fault velocity pulses, and other important features of the recorded earthquake motions at distances close to a finite fault. Rupture velocity, rupture initiation point, and slip-time functions over the ruptured area are the primary source parameters needed for the simulation of time-histories.

(2) Studies of previous earthquakes suggest that the actual fault rupture process is spatially and temporally complex. Therefore, in ground motion simulations, randomness is often utilized to characterize the source process. A source model is called a deterministic model if there is no randomness in the model parameters. A deterministic model is most appropriate for the regular part of a rupture process that dominates the generation of low-frequency waves. The jerky and irregular part of the rupture processes generates high-frequency waves and is usually characterized as a stochastic process because the rupture is usually too complicated to be described deterministically. It is generally believed that a hybrid source with both deterministic components (for low-frequency waves) and stochastic components (for high-frequency waves) is more robust than a deterministic or a stochastic process alone. Examples of simulation procedures that use stochastic and hybrid source models are given in paragraph B.3.

b. Wave propagation.

(1) Seismic waves propagating away from the ruptured fault undergo geometrical spreading, attenuation of wave amplitude due to inelasticity of the crust, reflection and refraction at the interface of distinct rock types, and scattering from lateral inhomogeneities. To simulate these path effects, a theoretical Green's function[1] can be calculated for a crustal model. The more complicated the crustal model, the more difficult and expensive to compute the Green's function numerically. The important factor determining the computational effort is the highest frequency of the simulated ground motions. Computational time increases almost as a cubic power of the maximum frequency of the simulations.

(2) Computation of the theoretical Green's function requires knowledge of the crustal parameters such as the compressional- and shear-wave velocities, density, and damping factor (or seismic Q factor, where $Q \approx$ 0.5/damping ratio). Different idealizations of the crustal parameter distributions in the earth's crust are being used for time-history simulations. In a homogeneous model, the crustal parameters are uniform throughout the crust, and the model has the simplest exact Green's function with $1/R$ geometrical spreading, where R is the hypocentral distance. This simple Green's function has been used in several stochastic simulation procedures (Boore 1983; Silva and Lee 1987). Green's function for a more realistic model consisting of horizontal layers of rock can also be calculated (Olson, Orcutt, and Frazier 1984; Luco and Apsel 1983). This layered model is now widely used in ground motion simulation practice to capture the first-order path effect of the earth's crust. When the site is in a sedimentary basin or is expected to experience topographic effects, then a crustal model involving lateral variation of rock properties and nonplanar geometry may be used. Complex wave phenomena (such as mode conversions, energy focusing, scattering, and diffraction) resulting from this type of large-scale heterogeneity are often important to the simulated ground motions. Green's function for this kind of complicated crustal model is feasible only via numerical methods such as finite element or finite difference, and these methods are time-consuming and are often limited to low-frequency calculations.

(3) Scattered waves from the small-scale heterogeneities of the earth's crust contribute significantly to the complexity of a recorded time-history. They prolong the ground motion duration, redistribute energies

[1] Green's function is the response of the earth to a seismic point source. It is a function of the site and source locations. A point source is the fundamental source that can be used as a building block to form a more general source.

among the three orthogonal components, and contribute to the spatial incoherence of ground motions. Lack of scattered waves in theoretical models led to the underprediction of strong motion duration of Northridge records by a factor of 1.3 and higher (Aki et al. 1995).

(4) An alternative to the theoretical Green's function is the empirical Green's function (Hartzell 1978, 1985; Irikura 1983; Hutchings and Wu 1990). An empirical Green's function is a recorded three-component set of time-histories of a small earthquake whose source mechanism and propagation path are similar to those of the design earthquake. This definition requires the empirical Green's function to be recorded at the site of interest, and its hypocenter occurs on the fault of interest. In keeping with the concept of Green's function, the magnitude of the event should be small enough that the source approximates a point source. The empirical Green's function is considered more realistic than the theoretical one in the high-frequency range (above 0.5 to 1.0 Hz); at lower frequencies, the signal-to-noise ratio is usually not good enough to make the recording useful. The main difficulty with the empirical Green's function approach is that it requires a sufficient number of them to cover the entire ruptured area. To overcome the lack of empirical Green's functions, approximations by extrapolating or interpolating the available empirical Green's functions are commonly made.

c. Ground motion simulations. Given the fault slip model and Green's functions, ground motions are computed using the representation theorem (Aki and Richards 1980; Hartzell, Frazier, and Brune 1978). The representation theorem involves a time convolution of the slip-time function with the Green's function and a surface integral of the convoluted Green's function over the rupture surface. The representation theorem allows the construction of ground motions from a finite source by integrating ground motions from simple sources (the convoluted Green's functions). In the computer implementation, the surface integral is typically approximated by a summation over a grid of points. Under this approximation, the simulation procedure simply sums a suite of Green's functions lagged in time. The time lag is the delay time caused by the rupture propagation plus the time needed for the seismic waves to travel from the corresponding point source to the site.

B.3 Examples of Simulation Procedures

a. A detailed review of some of the ground motion simulation methods currently in use can be found in reports published by Electric Power Research Institute (1995), Aki et al. (1995), and Schneider, Abrahamson, and Hanks (1996). Motivations behind these procedures are quite diverse. Some are intended mainly to provide an estimate of response spectra, and some are better suited to generating synthetic time-histories. In the following paragraphs, several simulation procedures are discussed, and examples of time-histories computed using these procedures are also given.

b. Boore (1983) developed a Band-Limited-White-Noise model for stochastic simulation of high-frequency ground motions. This simulation procedure does not generate ground motions from a given stochastic slip model. Instead, this procedure generates random white noise, multiplies it by a window function appropriate for the expected source duration, and then filters the windowed white noise to obtain a time-history having a band-limited Fourier amplitude spectrum specified by the T^2 source model (Brune 1970) and incorporating wave propagation effects of a homogeneous crust with $1/R$ geometrical attenuation. Silva and Lee (1987) use a similar formulation for the Fourier amplitude spectrum, but they use the phase spectrum from a natural time-history to generate the synthetic time-history. These stochastic procedures are well calibrated and validated for calculation of response spectra. However, it should be noted that the main motivation of these two stochastic methods is to simulate the average of the two horizontal response spectra, and they are not specifically aimed at generating a three-component set of time-histories that include the near-fault features and wave propagation effects. Related computer codes RASCAL (Silva and Lee 1987) and SMSIM (Boore 1996) are publicly available. In Figure B-1, time-histories obtained using these two programs are illustrated for an earthquake of magnitude M_w 6.7 at distance of 5 km. The RASCAL simulation uses the Fourier phase spectra from the Newhall record (USC station 56) of the 1994 Northridge earthquake to generate synthetic time-histories. The source model of these two simulation procedures is not a finite-source model because it does not explicitly simulate the propagating rupture of a finite source. Extensions to the finite-source model have been developed by Joyner and Boore (1986), Sliva et al. (1990), Silva, Chiou, and Somerville (1995), and Beresnev and Atkinson (1997).

c. Simulation procedures that use a hybrid slip model and Green's function of a layered crust have shown promise in generating realistic, broad-band three-component seismograms. Examples of this type of procedure include the composite-source approach (Zeng, Anderson, and Yu 1994), the self-similar slip model (Herrero and Bernard 1994; Joyner 1995), and the hybrid theoretical/empirical source approach (Somerville, Sen, and Cohee 1991; Somerville 1992). Two sets of three-component synthetic time-histories generated using the self-similar slip model are shown in Figure B-2. These time-histories were simulated at the Newhall recording station (USC Station 56) for the 1994 Northridge earthquake. Scattered waves are included in the simulations. A hybrid source model is used in the simulation of Set 1 that consists of a stochastic slip distribution superimposed on the deterministic slip model of the Northridge earthquake obtained by modeling the recorded velocity time-histories (Wald and Heaton 1994) at a large number of sites. As a result, Set 1 shows a greater resemblance to the actual Newhall record from the Northridge earthquake than does Set 2, where a slip model unrelated to the Northridge source model is used for the simulation. It is encouraging to see that both sets of synthetics exhibit the near-fault velocity pulse and the stronger fault-normal component (N 32° E) of the velocity pulse (Somerville et al. 1997) that is expected for a near-fault record.

B.4 Controls on Simulation Processes

a. Validation of simulation procedures. Before a procedure is used to generate ground motions for engineering applications, it should be formally validated. Systematic validation of a numerical procedure is needed to provide a check that the computational model of the procedure is adequate and to provide estimates of the modeling variability. Abrahamson, Somerville, and Cornell (1990) developed a method for validating numerical simulation procedures. The validation is accomplished by comparing how well the simulation procedure reproduces the characteristics of recorded motions from past earthquakes. Recently, this approach has been used to evaluate several simulation procedures by the Southern California Earthquake Center (Aki et al. 1995), Schneider, Abrahamson, and Hanks (1996), and the Multidisciplinary Center for Earthquake Engineering Research (1999). These validations have been based on the average of two horizontal response spectra. Strong-motion duration has been examined in these studies, but other time-domain characteristics (such as sequencing of various seismic phases and near-fault velocity pulse) have not been considered.

b. Production and adjustment of simulated time-histories. Simulated time-histories should be produced for the design earthquake conditions in terms of such factors as magnitude, fault dimensions, strike and dip angles of fault, style of faulting, and tectonic environment. Ground motion characteristics of these simulated time-histories should be similar to those estimated for the design conditions. If there are excessive differences, then one needs to scale the simulated time-history to the desired level and perform spectrum matching if necessary. Scaling and spectrum matching processes are described in Chapter 5. One also needs to make sure the desired special characteristics, such as the near-fault velocity pulse, are present in the simulated ground motions if conditions justify their existence.

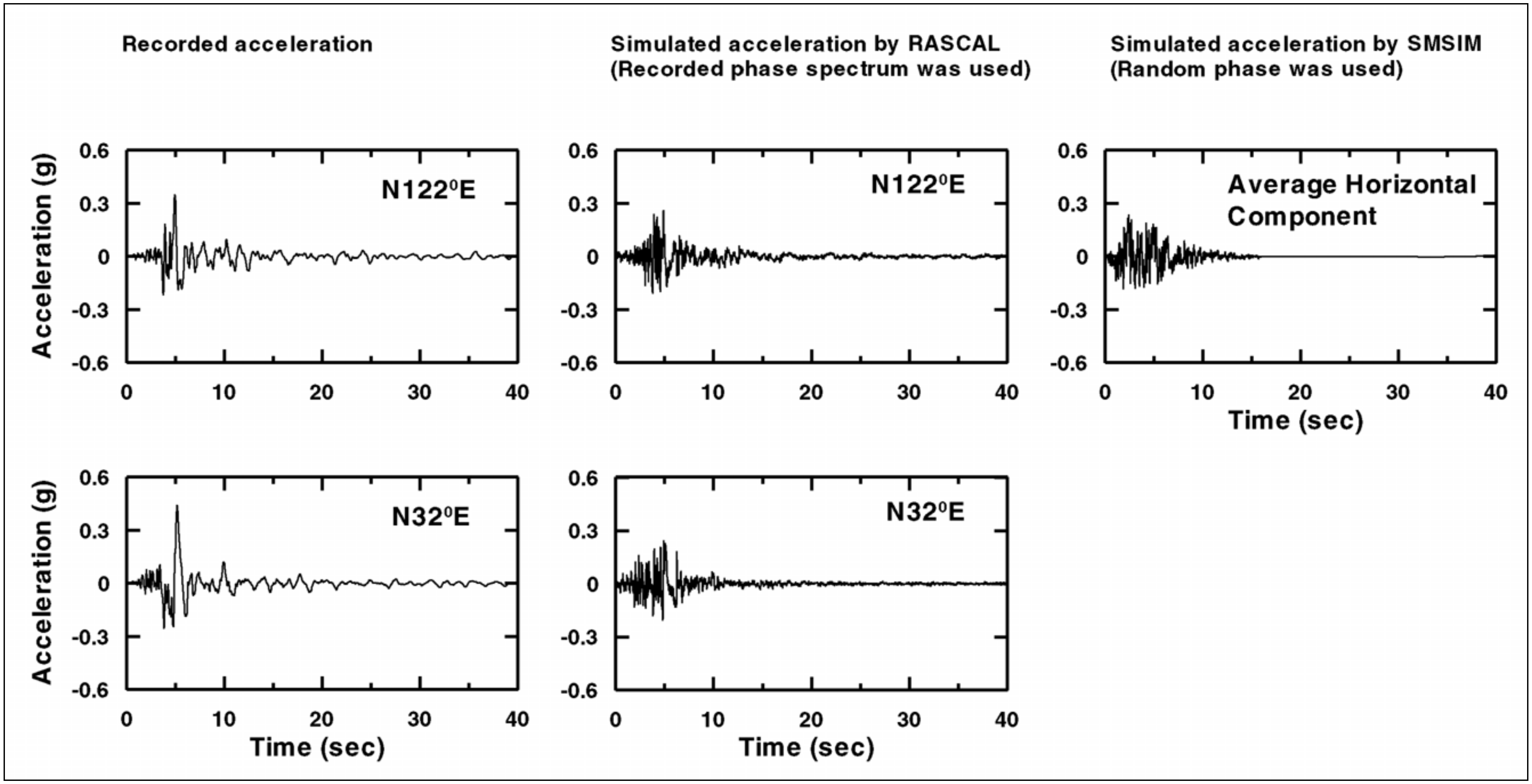

Figure B-1. Comparison of records simulated by stochastic procedure to the records at Newhall (USC Station 56) during the 1994 Northridge earthquake (Continued)

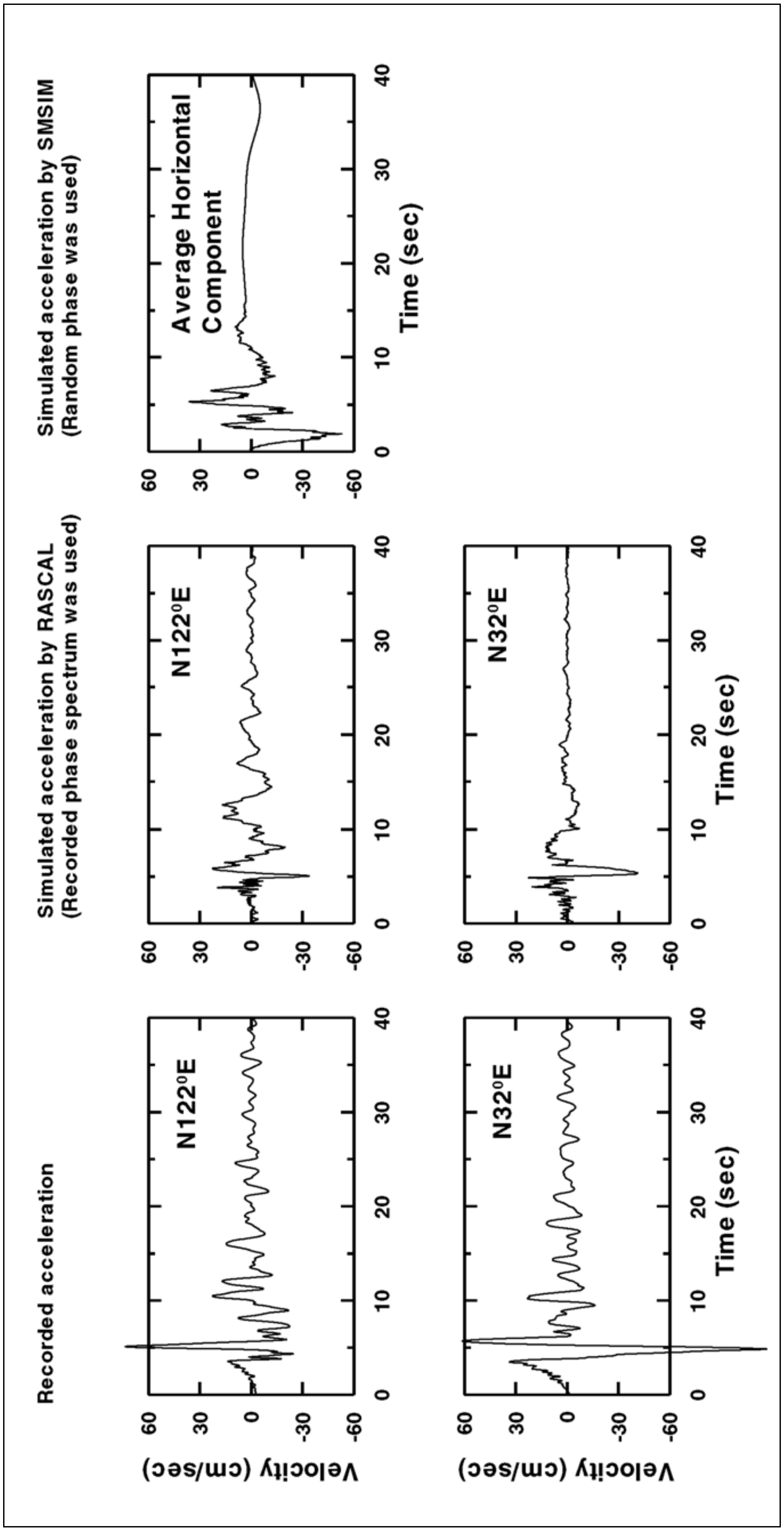

Figure B-1. (Concluded)

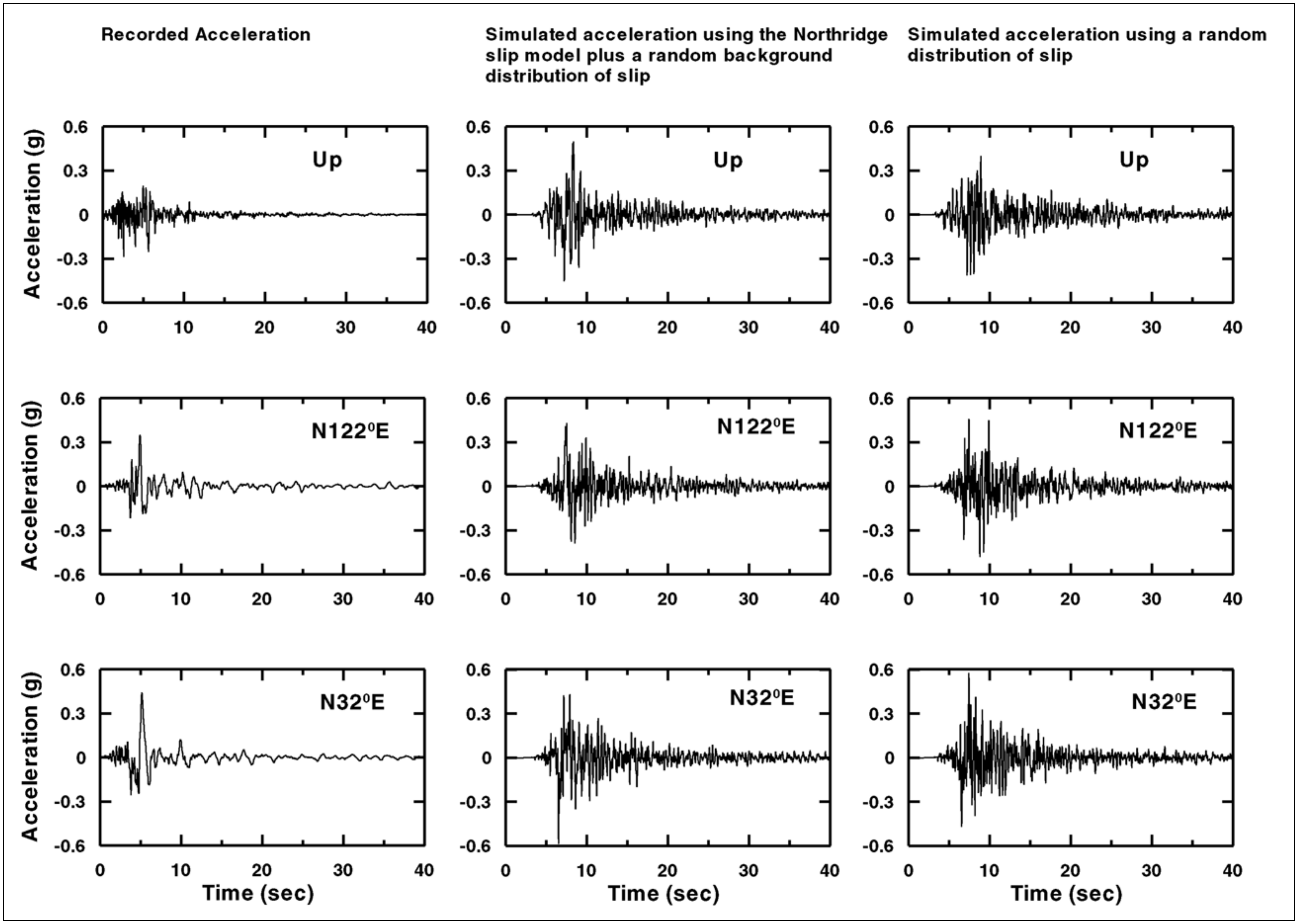

Figure B-2. Comparison of records simulated using a Green function/kinematic slip procedure to the records recorded at Newhall (USC Station 56) during the 1994 Northridge earthquake (Continued)

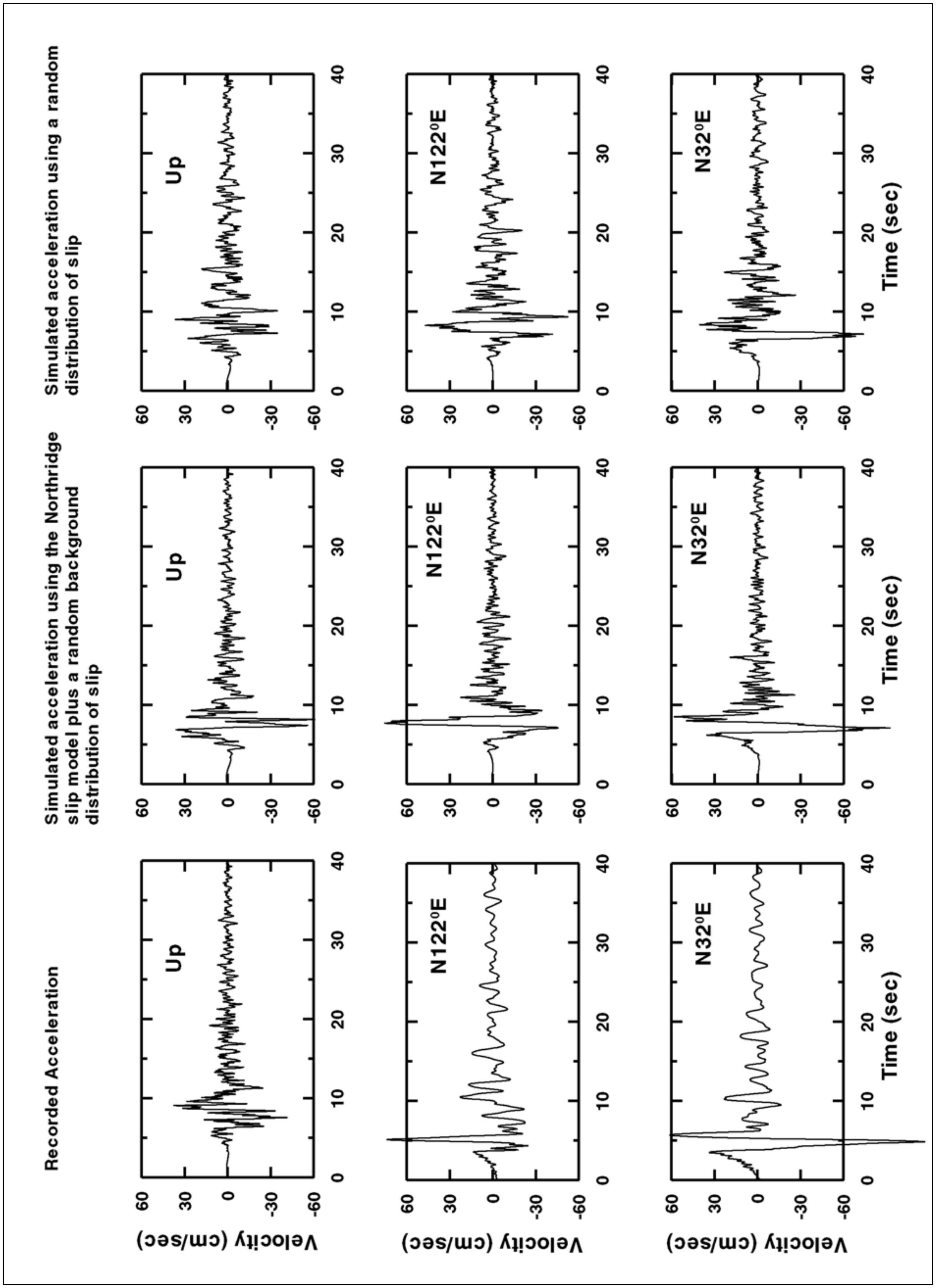

Figure B-1. (Concluded)