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PREDICTION OF DESIGN GROUND MOTIONS FOR LARGE EARTHQUAKES

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ABSTRACT

The objective of this study is to examine methodologies for predicting design ground motions from large earthquakes ($M_w \geq 6.5$) using random slip models and parametric variation of factors that influence the ground motions. To do so, we simulated broadband ground motion time histories for several moderate sized earthquakes using published slip models, rupture velocity and slip rise time obtained by modeling near-fault velocity records from these earthquakes. The slip models are generated using an algorith based on the characteristic features in slip models of strike-slip and thrust earthquakes occurring in western North America. The agreement between the recorded and simulated response spectra of these time histories was then quantified by measuring the mean bias and the mean standard error for each simulation over a period range between 5 to 0.03 sec. This investigation indicates that using many slip models (keeping other parameters fixed), it may be possible to obtain mean biases and mean standard errors similar to those mean biases and mean standard errors obtained from the known slip model. For example, we simulated broadband ground motion time histories at 25 stations located within the San Fernando Valley and Los Angeles basin which recorded the 1994 Northridge earthquake using the slip model, rupture velocity and slip rise time function of Wald and Heaton (1994; USGS Open-File Report 94-278; Pasadena). We did the same for 20 slip models keeping the other parameters fixed. Quantifying the mean bias and mean standard error, we found small differences in the results obtained using the slip model of the Northridge earthquake of Wald and Heaton (1994) and those predicted from the average of the random slip models. However, ground motions at individusl sites are quite sensitive to the choice of slip model and 2-D basin effects are useful to produce a better agreement in the response spectra at long periods. We have also investigated the level of ground motions at different sites within the Los Angeles basin due to a large M_w 7.9 earthquake on the San Andreas fault. The San Andreas fault is large and several hypocenters were used to simulate ground motions for examining the directivity effect. The predicted ground motions averaged over all the slip models and hypocentral locations showed good agreement with the empirical attenuation relation of Sadigh et al. (1993) for periods shorter than 0.25s, but produced large scatter above 1s which is mainly due to the variation in the rupture directivity. The simulation indicated that the directivity toward Cajon Pass from the Parkfield area can cause an increase in the level of ground motions at the Los Angeles basin sites. We are modifying these ground motions to include basin response effects through the use of 2-D relative site transfer functions (RSTF) using separate 2-D models for the RSTFs to represent different parts of the fault.

KEY WORDS

Ground motions, random slip models, hyocenters, directivity, basin effects, relative site transfer function (RSTF), Northridge and San Andreas earthquakes.

INTRODUCTION

Estimation of numerical broadband ground motions at a given site from a large scenario earthquake requires generation of random slip models that entail characteristic features of large earthquakes and the inclusion of propagation effects, rupture directivity, rise-time of source functions, path related scattering of seismic wavefield and other related parameters into the simulation method. The objective of this paper is to examine methodologies for predicting design ground motions for large earthquakes (Mw $\geq$ 6.5) using random slip models and parametric variation of various factors that influence the ground motions. The method that will be discussed in this paper is one in which time histories are simulated using a hybrid of two simulation methods, one for the long period ($f \leq 1$ Hz) using a deterministic approach and the other for the short-period ($f > 1$ Hz) using a semi-empirical approach (Somerville *et al.*, 1991; Saikia, 1993). The fault is discretized into many subfaults. In the long-period method, the source radiation is deterministic and the propagation effects from subfaults to receivers are computed using the frequency-wavenumber integration scheme. At high frequencies, empirical source functions are used for the source and the path effects are represented by culling contributions from significant rays computed using eneralized ray theory synthetics. The broadband time histories are simulated by a direct sum of the two resulting accelerograms. In addition to the modeling of strong motion time histories following several large earthquakes, including the 1978 Tabas (Saikia, 1994); 1987 Whittier (Saikia, 1993); 1985 Michoacan, Mexico and Valparaiso, Chile (Somerville *et al.*, 1991); the 1989 Loma Prieta and 1994 Northridge earthquake (Somerville *et al.*, 1996a) earthquakes; the high-frequency technique used in this method has successfully predicted levels of high ground motions observed during the January 17, 1994 Northridge earthquake for a hypothesized earthquake of Mw 7.0 on the Elysian Park thrust fault system with a fault geometry similar to that of the Northridge earthquake (Saikia, 1993).

The study on the Elysian thrust fault was a blind prediction of strong ground motions. The ground motions shown in Figure 1 display an agreement of the recorded peak accelerations from the Northridge earthquake with the simulated peak accelerations for the Mw 7.0 Elysian Park thrust earthquake and represent a successful blind test validation. We have used our broadband method to provide ground motion time histories for many engineering applications, including those at the sites of steel moment resisting frame buildings affected by the Northridge earthquake (Somerville *et al.*, 1995).

Other methods that exist for the simulation of strong motion time histories have been developed by Wennerberg (1990), Tumarkin and Archuleta (1994), and Zeng *et al.* (1994); and the methods differ from one another in the way the source is characterized and path effects are accounted.

In this paper, we are using the 1994 Northridge earthquake for further validation of our broadband simulation method in which we treat the source process of the Northridge earthquake as unknown. That is, we simulate ground motion time histories for a Northridge-like earthquake assuming that no slip distribution model for the earthquake is available. The only known parameters are the target seismic moment, source dimensions and fault orientation, including a structure model that is appropriate to account for the propagation effects. The objective of doing this is to assess the modeling uncertainty associated with the spectral responses and develop a procedure that can be useful in the blind prediction of ground motions.

In addition, we have also generated ground motion time histories at several sites lying within the Los Angeles basin for a scenario involving a large earthquake of magnitude M_w 7.9 (M_o=7.0x10^{24} dyne-cm) on the San Adreas fault. In this simulation study, we have used source models using the same procedure used for the Northridge earthquake. The objective of this study is to investigate how the ground motions within the Los Angeles basin are influenced by distribution of hypocenters and which portions of the San Andreas fault contribute strongly to the long-period signals.

NORTHRIDGE EARTHQUAKE - A BLIND PREDICTION

Following the Northridge earthquake of January 17, 1994, many studies were initiated which produced the slip distribution model for the earthquake (Wald and Heaton, 1994) and modeling of strong motion time histories (Somerville *et al.*, 1996a; Zeng *et al.*, (1996, personl communication). Somerville *et al.* (1996a) have used the source and crustal structure models of Wald and Heaton (1994) to simulate broadband time histories at sites located within the San Fernando and Los Angeles basins. Zeng *et al.* (1996) also used the source model of Wald and Heaton (1994), but generated an equivalent model to conform to their composite-source model and used the structure model slightly modified from Saikia (1993). In their study, they used propagation effects computed using the reflectivity/frequency-wavenumber method for the entire frequency band and introduced a scattering operator at high frequencies. Several other organizations, namely the University of California at Santa Barbara; University of Southern California, Los Angeles; University of Reno, Nevada; Pacific Engineering and Analysis, El Cerrito; and Woodward-Clyde Federal Sevices, Pasadena; which participated in the strong-motion program of the Southern California Earthquake Center (SCEC) modeled selected strong-motion time histories of the Northridge earthquake for validating their methods. All methods produced results consistent with the recorded motions, but the way the rupture models, rise time of source function and scattering of wavefields were included in these methods produced variations in the level and duration of the simulated time histories for the scenario earthquakes.

In this study, we assume the same source geometry of the Northridge earthquake as used in the above studies (for detail, see Somerville *et al.*, 1996). We used two velocity structures, one taken from Wald and Heaton (1994) and the other from Saikia (1993). For both models, we computed the generalized ray response for the direct P, SV and SH waves and one reflection from the interfaces below the source depths for simulating short-period accelerograms and frequency wavenumber responses for simulating long-period accelerograms. This was done for a suite of depths ranging from 6km to 21 km and epicentral distances ranging from 0.1 to 60 km. The rise time (τ) is scaled by the relation $\tau=1.79x10^{-9}xM_0^{1/3}$ where M_0 is in dyne-cm. This relation is based on the consistent modeling of observed ground motion data from many earthquakes and seems reliable.

In the synthesis of ground motion time histories for hypothesized earthquakes, one of the most important aspects of slip models is the distribution of slip over the fault plane. A large amount of work has been done in recent years in estimating the distribution of slip on the fault surface for several North American earthquakes. By isolating systematic features of these models, it is possible to develop algorithms for slip models useful for prediction of broadband accelerograms (Somerville *et al.*, 1995; Saikia and Somerville, 1996). Using this algorithm, we have generated 20 random slip models suitable for a thrust event. Some of these models are shown in Figure 2. We examined the extent to which the ground motions calculated from the slip model of an actual earthquake differ from those calculated from a random suite of slip models for the same fault geometry. To do this, we simulated time histories at 27 sites located in the San Fernando and Los Angeles basins using the slip model and crustal structure of Wald and Heaton (1994), and measured the bias and standard errors (Figure 3). This figure also shows the bias and standard errors for the simulated ground motions from 20 random slip models. We kept all other parameters fixed while using random slip models and used propagation effects represented by the structure model of Saikia (1993). The solid lines are the mean curves. At long periods, the mean bias curves are similar, but the mean bias curve for the Saikia structure model slightly under-predicted the mean bias curve obtained for the Wald and Heaton model at short periods, but the difference is not significant.

In the above experiment, we did not separate the rock sites from the soil sites or distinguish sites in the San Fernando valley from the sites in the Los Angeles basin. In addition, we treated every site uniformly with a shear wave velocity of 0.9km/sec at the surface. We expect the bias and standard error to be reduced if the simulation is done with a site specific crustal structure including the basin effects. Since this simulation is based on a one-dimensional crustal structure, bias and standard errors are related to the modeling uncertainties caused by site specific soil conditions and by the variation of the basin structure. It has already been shown that the bias can be significantly reduced by including the effect of basin structure, especially at long periods (see Graves, 1994; Somerville, Graves and Saikia, 1996b). The basin effect is included using the relative site transfer function technique proposed in Saikia *et al.* (1994).

One important finding of this study is that ground motions estimated using many random slip models is quite representative of the expected ground motions at a given site for the Northridge earthquake.

CHARACTERISTICS OF GROUND MOTIONS IN THE LOS ANGELES BASIN DUE TO A LARGE SAN ANDREAS EARTHQUAKE

As stated earlier, the objective of this study is to simulate broadband time histories due to a scenario involving a large earthquake of magnitude M_w 7.9 on the San Andreas fault at several sites lying along a profile in the Los Angeles basin (Figure 4) where long-period ground motions can be amplified which may be hazardous to high-rise buildings. The fault starts near Parkfield and extends roughly to Fort Cajon. A Mw 7.9 earthquake on this fault would be produced by the likely rupture of two linear segments, the north and south segments as shown in Figure 4, with strikes of 316° and 291°, respectively. In the synthesis of ground motion time histories, we discretize the fault surface of the north segment into a grid of 30 fault elements along strike and 5 elements down dip, each element having a length of 4 km and a width of 3 km. Similarly, the south segment has 45 subfaults along its length and 5 subfaults down dip. To distribute the seismic moment on these two segments, we first estimated the moment for each segment by adding the seismic moments using the actual slip on the subfaults. The ratio of the total seismic moments of the two segments was used to scale the target seismic moment of 7.94×10^{27} dyne-cm.

In this simulation study, we used 10 random slip models and three hypocenters in each segment. We also used an additional hypocenter at the location where the two segments met. Each segment had one hypocenter at its center. The north segment had two additional hypocenters at locations 30 km away on either side of the central hypocenter and similarly the south segment had two hypocenters at locations 45 km away on either side of its central hypocenter. We used this distribution of the hypocenters to investigate whether directivity would influence the predicted ground motions. Figure 5 shows time histories at Hollywood, one of several sites where ground motions are generated, for three hypocenters; namely Hyp.1, Hyp.4 and Hyp.7. for one slip model. Hypocenter Hyp.1 is located near Parkfield at 30 km from the northern edge of the north segment, Hyp.4 is at the location where the two segments met, and Hyp.7 is located near Lytle Creek at 45 km from the southern edge of the south segment. On the left of this figure, we show broadband time histories from the north segment; the center column shows time histories generated from the south segment; and the time histories plotted to the right are the sum of the corresponding accelerograms shown for the north and south segments. Only the velocity time histories are shown. While peak ground accelerations are dominated by the contribution from the south segment, peak ground velocities are influenced by both segments. While this is true for epicenters lying within the north segment, very little contribution comes from the north segment for both Hyp.4 and Hyp.7 hypocenters. This leads us to the conclusion that directivity towards the south from hypocenters within the north segment can increase the level of ground motions. Another notable feature of this study is the duration of time histories, especially at long period which is about 65s for Hyp.1 and is mainly due to the regional surface waves trapped within the crust. Strong long-period signals also appear on the velocity seismograms for Hyp.7 from the south segment, but the duration of this long-period waves is only 29s.

Figure 6 shows an example of the simulated horizontal pseudo spectral accelerations and pseudo spectral velocities computed using a 5% damping at Hollywood, averaged over all slip models with the empirical attenuation relation of Sadigh *et al.* (1993, solid thick line). In the upper two panels, we show the results for different hypocenters. The bottom two panels show the mean and one standard deviation for all slip models and hypocenters. The predictions show a large degree of scatter for periods above 1s which we conclude is mainly due to variation in rupture directivity effects.

We are modifying these ground motions to include basin response effects through the use of 2-D relative site transfer functions (RSTF) using separate 2-D models for the RSTFs to represent different parts of the fault. That is, we are using appropriate RSTFs representing the 2-D path effect for a certain number of subfaults. This way, we hope to capture the first-order 3-D effect in simulated ground motions. Our focus is on examining the effect of 2-D structure on engineering characteristics of ground motion, including the peak ground acceleration, peak ground velocity, spectral values and duration.

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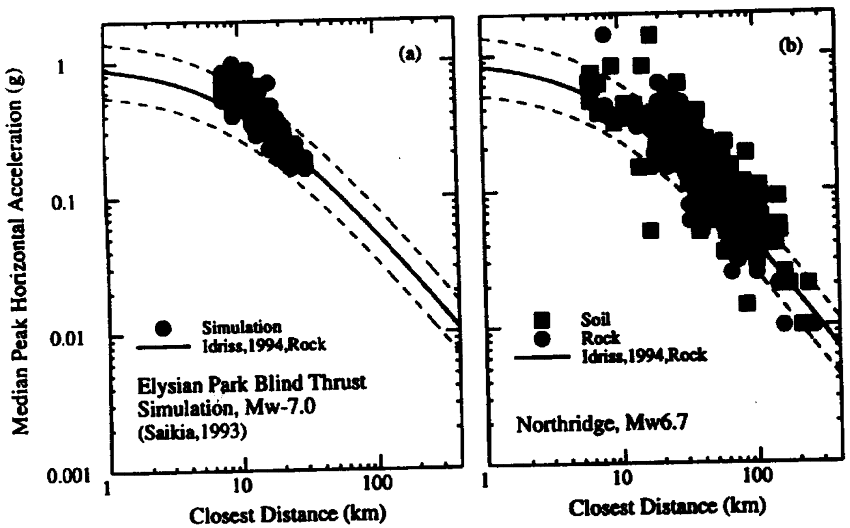

Figure 1. (a) Comparison of simulated ground motions for a Mw 7.9 earthquake on the Elysian Park blind thrust (Saikia, 1993) with the relation of Idriss (1991), (b) recorded peak accelerations of 1994 Northridge earthquake vs attenuation relation of Idriss (1991).

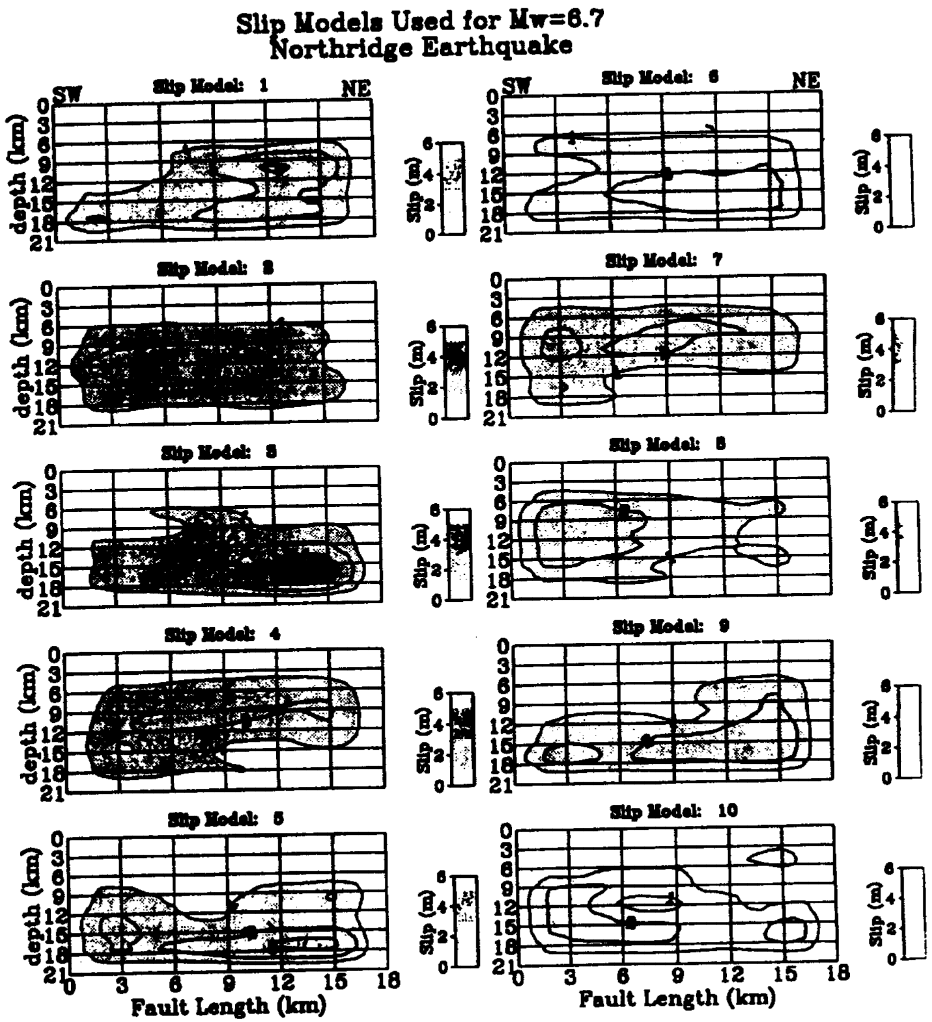

Figure 2. A subset of random slip models used to simulate ground motion time histories for the Northridge earthquake.

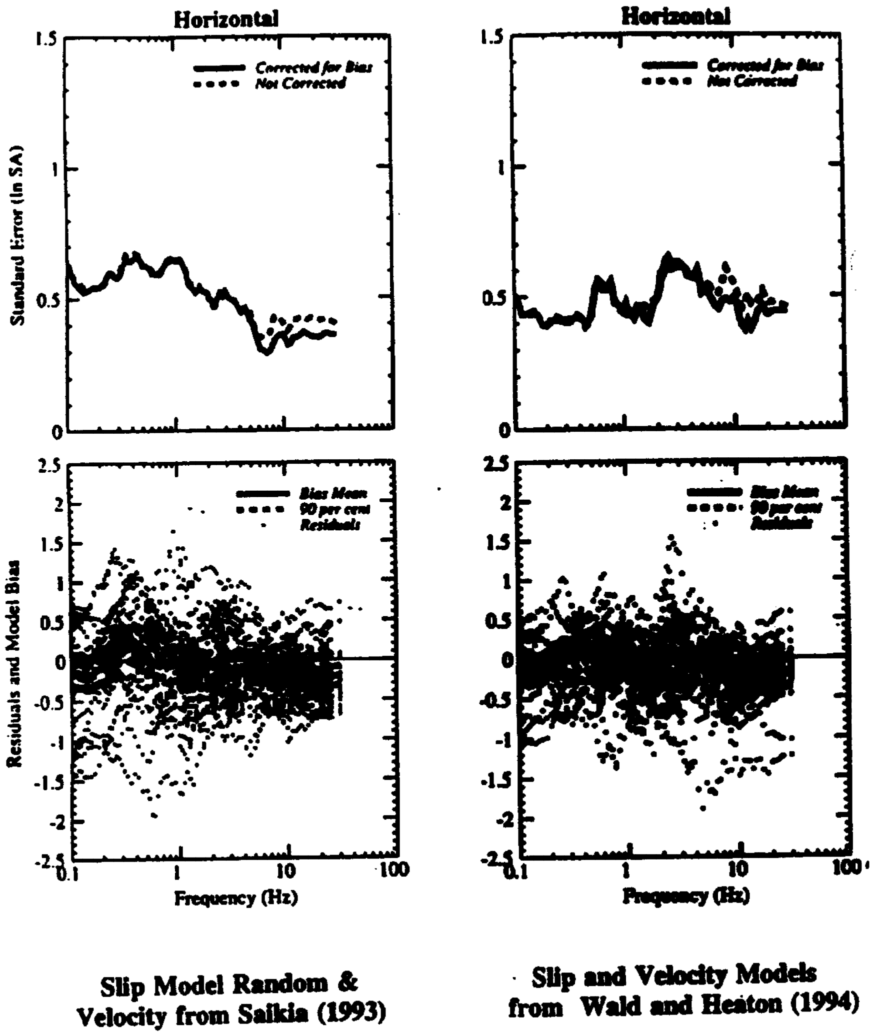

Figure 3. Comparison of residual and model bias using random slip models vs the slip model of Wald and Heaton (1994). A total of 27 stations was used. The solid lines are the mean curves.

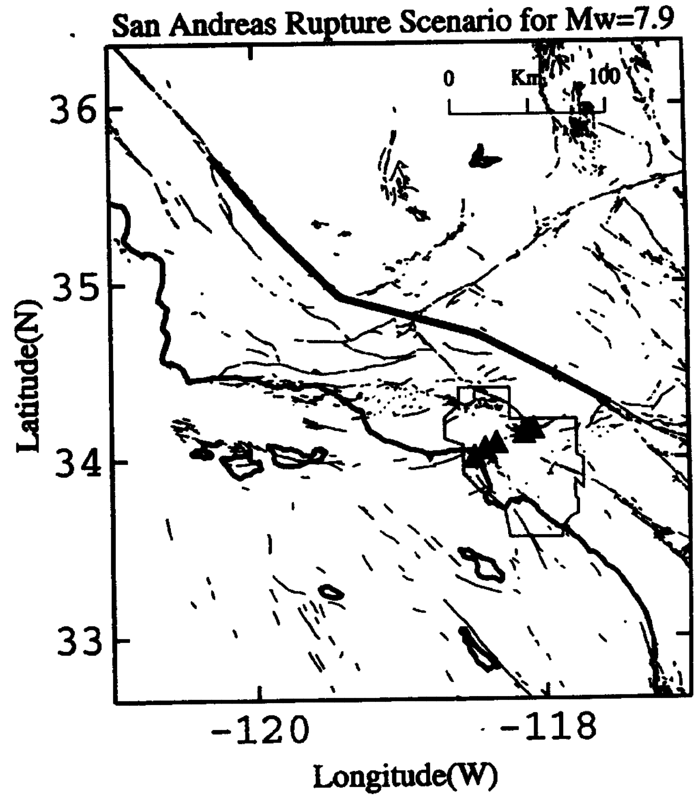

Figure 4. Map showing the scenario for the San Andreas earthquake. The solid line is the orientation of the San Andreas fault and triangles are locations of sites where the ground motion time histories are synthesized.

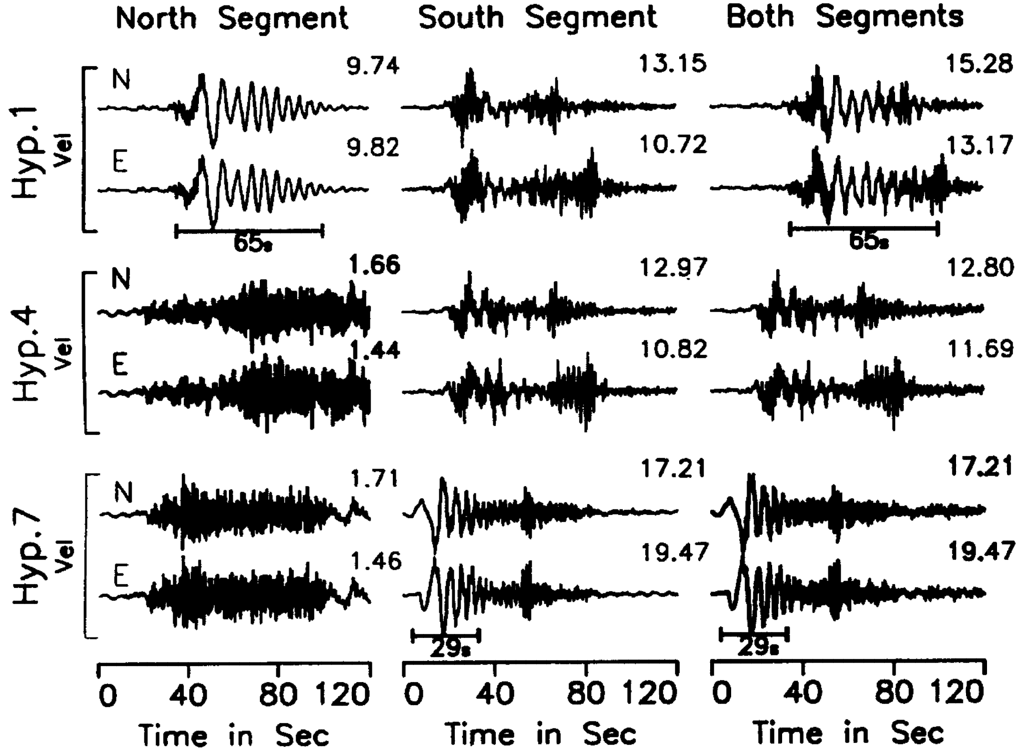

Figure 5. Boradband velocity time histories generated at Hollywood by treating the fault for a Mw 7.9 San Andreas earthquake as comprised of two segments. Note the duration of the long-period signals simulated by the north segment when hypocenter is near Parkfield, which reduces to half when the hypocenter is near Lytle Creek.

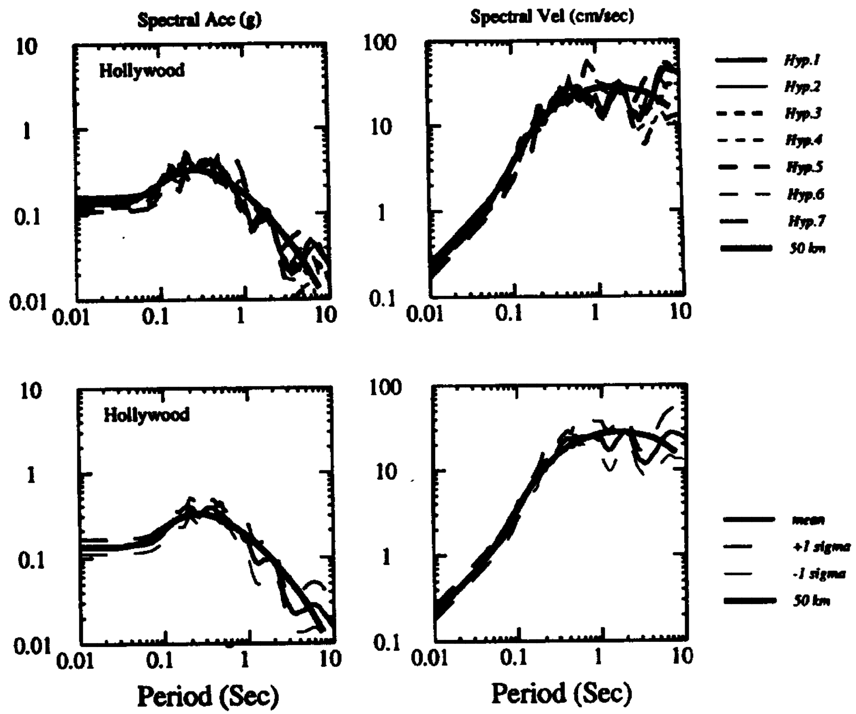

Figure 6. Simulated pseudo acceleration and velocity response spectrum at Hollywood due to Mw 7.9 San Andreas earthquake. Top panel: spectral estimates as a function of hypocenters; bottom panel: average spectral estimates using all realizations (10 slip models and 7 depths).