Analysis and Simulation of Earthquake Strong Ground Motion for Earthquake Engineering Applications

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Research Objectives

The objectives of this task are to conduct research on seismic hazards, and to provide relevant input on the expected levels of these hazards to other tasks. Other tasks requiring this input include those dealing with inventory, fragility curves, rehabilitation strategies and demonstration projects. The corresponding input is provided in various formats depending on the intended use: as peak ground motion parameters and/or response spectral values for a given magnitude, epicentral distance and site conditions; or as time histories for scenario earthquakes that are selected based on the disaggregated seismic hazard mapped by the U.S. Geological Survey and used in the NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings (BSSC, 1998).

We have developed the capability to synthesize/simulate earthquake strong motion over the entire frequency range, and for any source-receiver distance of engineering interest. The same models that are used to simulate strong ground motion can also be used to predict various measures of ground motion (e.g., $a_{max}$, $v_{max}$, $d_{max}$, $S_A$, $P_S$, etc.) that are important for earthquake engineering design. The synthesis/simulation and prediction techniques of strong ground motion that we developed properly account for site effects and are valid for sites both near an extended fault/source as well as at far-field.

Originally, our goal was to focus our prediction efforts on Eastern North America (ENA). However, responding to the growing needs of MCEER researchers, we expanded the scope of our work to include the entire continental United States. Specifically, we calibrated our models to provide earthquake ground motion modeling and prediction capabilities for three types of tectonic regimes that characterize the continental United States: *active* tectonic regime (e.g., California), *extensional* tectonic regime (e.g., Nevada), and *low seismicity* tectonic regime (ENA).

The ‘tools’ that we developed are very practical (so that they can be used with ease by earthquake engineers), yet they are grounded on solid physical models that properly account for all the important aspects of seismic wave generation at the source, as well as propagation path and site effects.
In parallel to the above efforts, we have performed basic research that focused in the areas of earthquake source radiation and local site effects. Specifically, we have developed mathematical models that can be used, for instance, to mathematically represent the sub-events that compose large earthquake events, and we have investigated and compared various methods (e.g., “coda wave” methods, the “standard spectral ratio” method, the “H/V ratio” method) that have been proposed to quantify local site effects.

Strong Motion Synthesis Techniques

Our task is the synthesis of strong ground motion input over the entire frequency range of engineering interest. There are two approaches for modeling earthquake strong motion:

1. The Stochastic (Engineering) Approach, according to which, earthquake motion (acceleration) is modeled as Gaussian noise with a spectrum that is either empirical, or based on a physical model (such as the “Specific Barrier Model”) of the earthquake source. This approach is expedient and therefore cost-effective, and has been extensively used in the past by engineers (using empirical spectra) and recently by seismologists (using spectra derived from physical models of the source). The intent of this approach to strong motion simulation is to capture the essential characteristics of high-frequency motion at an average site from an average earthquake of specified size. Phrasing this differently, the accelerograms artificially generated using the Engineering Approach do not represent any specific earthquake, but embody certain average properties of past earthquakes of a given magnitude.

2. The Kinematic Modeling Approach was developed by seismologists. In this approach, the rupture process is modeled by postulating a slip function on a fault plane and then using the Elastodynamic Representation Theorem to compute the motion (e.g., Aki and Richards, 1980). There are several variants of this approach depending on whether the slip function (i.e., the function that describes the evolution of slip on the fault plane) and/or the Green functions are synthetic or empirical. The Kinematic Modeling Approach involves the
prediction of motions from a fault that has specific dimensions and orientation in a specified geologic setting. As such, this approach more accurately reflects the various wave propagation phenomena and is useful for site-specific simulations.

**Stochastic (Engineering) Approach**

Recognizing that the Stochastic Approach for synthesizing earthquake strong motion time histories is the most expedient method, ground motion synthesis efforts were initiated following this approach. We developed computer programs that may be used to:

1. Estimate the mean/expected values of peak ground motion parameters (i.e., peak acceleration, peak velocity and peak displacement), and spectral response amplitudes, based on Random Vibration Theory (e.g., Rice, 1944, 1945; Cartwright and Longuet-Higgins, 1956; Shinozuka and Yang, 1971; Soong and Grigoriu, 1993);
2. Simulate ground motions using the Stochastic (Engineering) Approach briefly described above (e.g., Shinozuka and Jan, 1972; Shinozuka and Deodatis, 1991; Boore, 1983; Grigoriu, 1995);
3. Simulate ground motion time histories that are compatible with prescribed response spectra using the Spectral Representation Method (Shinozuka and Deodatis, 1991; Deodatis, 1996).

Various earthquake source models that have been proposed in the published literature [such as the Specific Barrier Model (Papageorgiou and Aki, 1983a,b; 1985, 1988) and the $\omega^2$-model (Brune, 1970; Frankel et al., 1996)] have been implemented (and are provided as options) in the above mentioned computer codes. Site effects are taken into account in the simulated ground motions by using the site classifications of the 1997 NEHRP Provisions (BSSC, 1998).

Of all the source models, we favor the Specific Barrier Model because it provides the most complete, yet parsimonious, self-consistent description of the faulting processes that are responsible for the generation of the high frequencies, and at the same time provides a clear and unambiguous way of how to distribute the seismic moment on the fault plane. The latter requirement is necessary for synthesizing near-fault (i.e., in the vicinity of an extended source/fault) ground motions.

We calibrated the Specific Barrier Model using three different extensive databases of recorded earthquake strong motions reflecting the characteristics of three types of tectonic regimes that characterize the continental United States: (1) active tectonic regime (e.g., California), (2) extensional tectonic regime (e.g., Nevada), and (3) low seismicity tectonic regime (ENA). Thus, the “scaling law” of the source spectra (i.e., how the spectral content of the seismic waves radiated by the source varies with earthquake magnitude) was established for each one of the above tectonic regimes. Such a “scaling law” is necessary for the prediction/simulation of ground motion at any site of any one of the above tectonic regimes.
Figure 1 displays the ‘Magnitude-Distance’ space of the above datasets, while Figures 2, 3 and 4 summarize the results of the fitting of the Specific Barrier Model to the datasets of each one of the tectonic regions. Specifically, Figures 2 and 3 show the source spectra of the Specific Barrier Model fitted to the data of each one of the tectonic regions assuming “self-similarity” (Figure 2a) and disregarding self-similarity (Figure 3a). [According to the assumption of self-similarity, all earthquake events may be specified by a single parameter, say seismic moment $M_0$, and that small events are similar to large ones. Self-similarity implies “geometric similarity,” i.e., length $L$, width $W$ and slip $\Delta u_0$ all scale as $\sim M_0^{1/3}$, and “physical similarity,” i.e., all nondimensional products of source parameters are the same, while the rupture velocity is constant and all parameters with the]
dimension of time scale as \( \sim M_0^{1/3} \) (Aki 1967). Figures 2b, c, d and 3b, c, d display the corresponding inter-event residuals. Clearly, the data reveal that the assumption of self-similarity does not hold in the strict sense for the active and extensional tectonic regimes (notice the linear variation of the inter-event residuals with \( M_w \)). Finally, Figure 4 displays the behavior of the residuals for each one of the tectonic regimes. The purpose of plots such as Figure 4 is to reveal any significant biases in the fitting, or any trends with earthquake magnitude and/or source-station distance. The behavior of the residuals shown in Figure 4 confirms that the fitting of the Specific Barrier Model to the data is satisfactory.

As we pointed out above, the Specific Barrier Model makes it
possible to simulate, in a consistent and physically plausible manner, near-fault ground motions. This feature of the model is especially significant for relatively densely populated urban areas located in the midst of tectonically active regions such as the Los Angeles (LA) Basin. For instance, it has been estimated that, for a profile of sites crossing the LA Basin, the 10%-in-50 yr exceedance level (which is typically used in design) is generally dominated by $M_W \geq 6.75$ events within $\sim 20$ km of the site (Field et al., 2000). The fault-normal component (i.e., the component normal to the strike of the fault; “strike” is the direction defined by the intersection of the fault plane with the free surface of the earth) of ground velocity recorded at a station in the vicinity of a fault and located in the forward (relative to the propagating rupture front) direction is characterized by a pulse of intermediate to long period. Such near-fault velocity pulses have intense amplitude ($A \sim 100$ cm/sec).
and are the result of directivity (for appropriate source mechanisms, such pulses may be the result of the combined effects of directivity and permanent translation; for a complete and detailed discussion see Mavroeidis and Papageorgiou, 2003). Figure 5 displays near-fault strong ground motion records with ‘distinct’ velocity pulses.

We have proposed a simple, yet effective, analytical model to mathematically represent such near-fault directivity pulses. The model adequately describes the impulsive character of near-fault ground motions both qualitatively and quantitatively. In addition, it can be used to analytically reproduce empirical observations that are based on available near-source records. The input parameters of the model have an unambiguous physical meaning. The proposed analytical model has been calibrated using a large number of actual near-field ground motion records. It successfully simulates the entire set of available near-fault displacement, velocity and, in many cases, acceleration time histories, as well as the corresponding deformation, velocity and acceleration response spectra. Figure 6 shows a sample of synthetic waveforms (red trace) fitted to actual near-fault records (gray trace) along with the corresponding 5% damped elastic response spectra.

The same mathematical model has been exploited for the investigation of the elastic and inelastic response of the single-degree-of-freedom (SDOF) system to near-fault seismic excitations (Mavroeidis et al., 2004). A parametric analysis of the dynamic response of the SDOF system as a function of the input parameters of

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Figure 4. Summary of the behavior of residuals for (a) the interplate, (b) the extensional, and (c) the intra-plate tectonic regions based on the “non-self-similar” source scaling. The figures display as a function of oscillator period the (i) mean residual bias (top), and the slope of a straight line fitted through the residuals plotted vs. (ii) log-distance (middle) or vs. (iii) magnitude (bottom). In all cases, the residuals are near zero and exhibit no significant trends.
the mathematical model was performed to gain insight regarding the near-fault ground motion characteristics that significantly affect the elastic and inelastic structural performance.

A parameter of the mathematical representation of near-fault motions, referred to as “pulse duration” \( (T_p) \), emerges as a key parameter of the problem under investigation. Specifically, \( T_p \) is employed to normalize the elastic and inelastic response spectra of actual near-fault strong ground motion records. Such normalization makes feasible the specification of design spectra and reduction factors appropriate for near-fault ground motions. The “pulse duration” \( (T_p) \) is related to an important parameter of the rupture process referred to as “rise time” \( (\tau) \) that is controlled by the dimension of the sub-events (“barrier interval” \( 2\rho_0 \)) that compose the main-shock.

From the variation of \( T_p \) vs “moment magnitude” \( (M_w) \) (Figure 7a) and the scaling of the sub-event size \( (2\rho_0) \) with \( M_w \) (Figure 7b), we inferred that \( \tau \sim (1/2)T_p \). [The “rise time” \( (\tau) \) is the time that it takes for a representative point of the fault plane to complete its slip.]

Parameters \( T_p \) and \( A \) can be utilized to effectively normalize the elastic and inelastic response spectra of SDOF systems subjected to actual near-fault records. Such normalization makes feasible the specification of normalized design spectra for near-fault ground motion excitations of different earthquake magnitude ranges. The Veletsos-Newmark-Hall equations for reduction factors can be used for near-fault ground motions provided that normalized response spectra are used along with appropriately selected values of \( (T_n/T_p)_{a} \), \( (T_n/T_p)_{b} \), and \( (T_n/T_p)_{c} \). Average elastic spectra for near
fault ground motions (along with appropriate reduction factors for various values of ductility) have been proposed by Mavroeidis et al. (2004).

Analytical modeling makes it feasible to make educated conjectures about the character of near-fault pulses for tectonic regions (such as Eastern North America) for which such recordings are very few or completely lacking. For example, for Eastern North America (ENA), various investigators (e.g., Halldorsson and Papageorgiou, 2004) have concluded that the value of the stress parameter (local stress drop) that controls the high
frequency amplitudes of source spectra of intra-plate sources is higher when compared to that of inter-plate sources. Furthermore, it has been conjectured that the rise-time of intra-plate sources may be shorter when compared to that of inter-plate events of comparable size. In view of these observations, one would expect the near-fault velocity pulses to be “sharper” (i.e., to have larger amplitude and shorter duration) when compared to the corresponding pulses of inter-plate events of comparable magnitude. Halldorsson et al. (2003) explored the above hypothesis by investigating the very limited relevant strong motion database, and concluded that the above conjecture appears to be valid. This result, however, is very tentative and requires more data to be firmly established or refuted.

**Kinematic Modeling Approach**

In the 1990’s [when MCEER was known as the National Center for Earthquake Engineering Research Center (NCEER)] we had developed a computer code implementing a method, referred to as the “Discrete Wave-number Method,” originally proposed and developed by Bouchon and Aki (1977) and Bouchon (1979). The method is a very efficient computational technique that can be used to compute the wave-field [i.e., displacements and differential motions (i.e., strains)] generated by a seismic source (such as a shear fault) in layered homogeneous isotropic elastic half-space (for a discussion of the method see Spudich and Archuleta, 1987; Bouchon, 2003). We have used the code to compute the wave field generated by the 1994 Northridge earthquake (Zhang and Papageorgiou, 1995, 1996; Papageorgiou, 1997). [Figure 8, which displays snapshots of the horizontal component of displacement of the 1994 Northridge, California earthquake (taken from Papageorgiou 1997; originally presented by Zhang and Papageorgiou, 1995), was generated using our computer code.] Recently,
Figure 8. Snapshots of the Horizontal Component of Displacement of the 1994 Northridge, California Earthquake using the Rupture Model of Wald et al. (1996)
Bouchon (1997) extended the “Discrete Wave-number Method” to compute the evolution of stress on the causative fault plane of an earthquake. In order to investigate the relation of the near-fault velocity pulse waveform to the slip and stress spatio-temporal history over the fault plane, we proposed to investigate...

Figure 9. Recorded (black trace) and synthetic (gray trace) near-fault ground motion time histories and S-wave isochrones for selected stations that recorded the 1989 Loma Prieta earthquake. Tomographic images of the static slip offset, static stress drop, and strength excess along the strike and dip directions are also illustrated.
events that produced near-fault strong motion recordings and for which reliable tomographic images of the evolution of slip have been inferred by inversion. In order to accomplish the above-stated goal, we implemented (Mavroeidis, 2004) Bouchon’s (1997) method for the computation of the spatio-temporal evolution of various measures of stress change (e.g., strength excess, dynamic stress drop, static stress drop) over the fault plane, and we related the slip distribution and the above measures of stress change to the near-fault velocity pulses using the concept of “isochrone” curves. Figure 9, taken from Mavroeidis (2004), displays tomographic images of the static slip offset, static stress drop, and strength excess over the fault plane along with recorded (black trace) and synthetic (gray trace) near-fault ground motion time histories and $S$-wave isochrones for selected stations that recorded the 1989 Loma Prieta earthquake. Images such as Figure 9 reveal the factors that contribute to (and therefore control) the generation of near-fault intense pulses.

Mathematical Models of Sub-events

In a series of papers (Dong and Papageorgiou, 2002a;b; 2003; 2004), we have developed closed-form mathematical expressions regarding the seismic radiation of a general family of crack models. Such models can be used to represent sub-events of a main earthquake event in source models such as the “Specific Barrier Model.” Such mathematical models are very useful because, among other things, they provide a quantitative relation between important source parameters (such as “stress drop” $\Delta \sigma$, rupture front geometry (curvature) and kinematics (rupture velocity variations)) and the radiated seismic field. For example, such models quantify the directivity effects of rupture front kinematics on the radiated acceleration pulses at nearfield, and thus complement the model that we proposed (and summarized above) for the near-fault velocity pulses. Figure 10 shows the acceleration pulses (Figure 10b) radiated by an asymmetrical circular crack model (Figure 10a) when the rupture propagation is decelerated and eventually arrested at the periphery of the crack.

![Figure 10](image-url)
Overarching Center-wide Cross Program Research Activities

Site Effects

The unprecedented recorded database generated by the 1999 Chi-Chi, Taiwan, earthquake and its aftershocks provides a unique opportunity to investigate site effects on earthquake ground motion. We analyzed strong motion data [recorded by the seismic network of Taiwan Strong Motion Instrumentation Program (TSMIP)] during the main event and 33 aftershocks of 1999 Chi-Chi, Taiwan, earthquake (Ml 7.6) (Figure 11) and short period data [recorded by the network of Central Weather Bureau Seismic Network equipped with 3-component Teledyne-Geotech S-13 seismometers; this data set consists of 5,499 records generated by 108 events (2.90 < Ml < 4.97)] (Zhang and Papageorgiou, 2004a). The strong motion data were grouped according to peak ground acceleration (PGA). Site amplification was inferred using three techniques: (1) Generalized Inversion of S-waves; (2) H/V method (i.e., the ratio of the spectral amplitudes of the horizontal and vertical components of motion); (3) Coda-wave inversion. Coda waves from both short period and strong motion data were used. As reference sites for the generalized inversion, we selected stations that have been classified as belonging to site class B. The site amplification estimates obtained using the abovementioned three different techniques are reasonably close to each other for weak motions (< 0.1 g). The presence of nonlinearity, due to the intensity of ground motion, was clearly identified at several stations that recorded both strong (> 0.2 g) as well as weak (< 0.1 g) motions (Figure 12). Finally, we correlated site amplification with geologic formation (i.e., classification based on geologic age), and NEHRP classification, and we concluded that the latter classification provides the smaller scatter.

Using the short period data, we also investigated the attenuation characteristics of Taiwan (Zhang and Papageorgiou, 2004b). Specifically, using the “coda decay curve,” we estimated the coda attenuation $Q_c$, and while using the “Coda Normalization Method” we estimated the $S$-wave attenuation $Q_s$. Furthermore, we used the


Figure 11. Distribution of the stations of the seismic network of Taiwan Strong Motion Instrumentation Program (TSMIP) that recorded the 1999 Chi-Chi earthquake and its most significant aftershocks (indicated by stars) on a geological map of the island of Taiwan.
“Multiple Lapse Time Window” (MLTW) method to resolve the total attenuation $Q_t$ into scattering $Q_s$ and intrinsic $Q_i$ attenuation, as well as the scattering coefficient $g_0$ (for a description of the above methods of data analysis, we refer the reader to Sato and Fehler, 1998). Based on the results of our analysis, we observed that the coda attenuation $Q_c$ is close to the intrinsic attenuation $Q_i$, which agrees with the results of previous investigations. The total attenuation $Q_t$ is close to that obtained from the Coda Normalization Method. The scattering coefficient is estimated to be $\sim 4.8 \cdot 10^{-3}$ km$^{-1}$, consistent with (yet closer to the lower side of) estimates of this parameter for other tectonically active regions (Figure 13). Attenuation and scattering characteristics (and corresponding parameters) of a region are necessary input in the simulation of realistic Green’s functions of
the lithosphere, which, in turn, are necessary for the synthesis of earthquake ground motion.

Conclusions and Future Research

We have developed simple, yet effective, models for analyzing and simulating strong ground motion for earthquake engineering applications. Using the “Stochastic (Engineering) Approach,” the simulated time series may account for near-fault effects, if necessary. However, the simulation techniques that we have developed so far do not account for the long-period surface waves (usually $T \approx 3$ sec and longer) that are generated in a sedimentary basin, (i) from the conversion of body waves at the edges of the basin, if the seismic source is located outside the basin (e.g., 1952 Kern County; 1971 San Fernando; 1990 Upland; 1992 Landers; 1994 Northridge; 1999 Hector Mine), or (ii) from channeling of seismic energy in the waveguide of the sediments in the form of surface waves, if the source is located in the basin (e.g., 1979 Imperial Valley earthquake). Such waves affect the long-period structures, such as long-span bridges, and high-rise buildings. From the above list of earthquakes, it is evident that basin-edge-generated surface waves are an important consideration for long-period structures located in the LA Basin.

We would like to expand the capability of our simulation techniques and incorporate such waves in the synthetic motions for sites where the conditions are conducive for such waves. The technique that we propose to use is based on the physics of surface wave propagation and incorporates the dispersion characteristics of the sedimentary deposit (i.e., group and phase velocities). Incorporation of such waves, with the appropriate arrival time, in the synthetic motions will render the simulated time-series non-stationary with respect to their frequency content. In the past, earthquake engineers proposed simulation techniques of non-stationary processes (e.g., Grigoriu et al., 1988). We would like to explore how our
technique, that is motivated by the physics of the process, relates to the abovementioned phenomenological techniques.

Finally, using the models of ground motion that we have developed, we are currently investigating the response of structures (including soil-structure-interaction effects) to near-fault ground motions and basin-generated surface waves. Specifically, reasoning that the near-fault intense pulses may be associated with intense rotational motions about a vertical axis (Bouchon and Aki, 1982; Zhang and Papageorgiou, 1996; Gomberg, 1997; Mavroeidis, 2004), we are currently investigating the torsional response of structures to such motions (Figure 14; Meza-Fajardo and Papageorgiou, 2004). Similarly, recognizing that the basin-generated surface waves may be detrimental for long period structures, we have developed an analytical model of a suspension bridge tower-pier system and are currently investigating its response to such waves (Dong and Papageorgiou, 2004; manuscript in preparation).

Acknowledgements

This research was primarily supported by the Earthquake Engineering Research Centers Program of the National Science Foundation, under award number EEC-9701471 to the Multidisciplinary Center for Earthquake Engineering Research. This support is gratefully acknowledged.

References


