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MULTIDISCIPLINARY CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
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Proceedings of the MCEER Workshop on Ground Motion Methodologies for the Eastern United States

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Table of Contents

APPENDICES

Table of Contents (cont'd)

* *Appendices B through J are provided on MCEER's web site at http://mceer.buffalo.edu.*

List of Illustrations

List of Illustrations (cont'd)

List of Tables

SECTION 1
INTRODUCTION

In October 1997, the Multidisciplinary Center for Earthquake Engineering Research (formerly the National Center for Earthquake Engineering Research) and the Federal Highway Administration (FHWA) sponsored a two-day workshop, *Ground Motion Methodologies for the Eastern United States*, to evaluate ground motion modeling methods applicable in the eastern U.S. The predictive methods were to be assessed for their ability to produce time histories appropriate for use in engineering applications. The intent of the workshop was not to rank various modeling methodologies, but rather to evaluate the state-of-the-art for strong ground motion prediction in the region and the variability of time histories from different modeling methods. Further, the workshop served to introduce the participants to the concept of formal model validation and thence application to develop synthetic motions. This focus on practicality responded to the user community's need to evaluate the credibility of synthetic time histories developed for specific projects and the lack of criteria on which to base these evaluations.

Two issues were paramount in the evaluation of the time histories: the peak amplitudes of the ground motion and the non-stationary character of the time history. The models were assessed against the following measures:

- the ability of the methods to predict the amplitude of the ground motion (median and variability) expressed as elastic response spectra;
- their ability to define the non-stationary characteristics of the time history expressed as duration of the acceleration, velocity and displacement;
- whether synthetic time histories require further scaling and, if so, what the scaling rules are;
- what means can be used to evaluate synthetic time histories to ensure they are reasonable.

Ultimately, the workshop resulted in recommendations as to the seismological community's ability to predict absolute levels of expected shaking and to judge whether synthetic motions required subsequent modification.

1.1 User Needs

The engineering community involved in the seismic assessment of eastern U.S. (EUS) facilities looks to the seismological community to define ground motion time histories for seismic evaluation of structures. In previous highway projects, time histories developed by different groups have been significantly different in both amplitude and waveform. The engineering community requires criteria to evaluate the adequacy of synthetic ground motions, whether defined by time histories or response spectra, or other ground motion characteristics. They also require guidance regarding use of finite fault modeling for near-fault motions. Finally, they require a cost-effective approach to develop motions for standard application.

Because of the scarcity of recorded EUS strong ground motions for comparisons, the engineering community lacks measures against which they may judge the attributes of synthetic time histories. Currently available attenuation relations provide estimates of the response spectral values, but for evaluating time histories, estimates of the peak ground velocity and peak ground displacement are also needed. Additionally, measures of non-stationarity are needed to check the synthetic time histories: acceleration (velocity, and/or displacement) duration, and/or the slope of a Husid plot for the motion, and a recommendation on one- or two-sided displacement histories.

Practitioners also need cost-effective methods to develop ground motions for use in typical applications. Site-specific modeling can be costly and generally is warranted only for the analysis of critical facilities. A standard library of time histories for EUS earthquakes is needed for use in engineering evaluations. This library should include well documented motions for a few representative cases and guidelines on acceptable methods of scaling them.

1.2 Validation and Simulation Studies

The goal of the NCEER/FHWA workshop was not to set target spectra or other acceptability criteria, but rather to evaluate synthetic time histories resulting from various predictive models. The workshop focus on methods of predicting strong ground motion was the first step in addressing the needs of the engineering community by assessing the capabilities of available numerical simulation procedures. An element of this effort consists of a validation exercise for each modeling method to check model calibrations and test parameter sensitivities. A suite of simulations from each method is needed to estimate the median ground motion and the variability.

This approach has been adopted in several recent studies including the 1990 Diablo Canyon Long Term Seismic Program (LTSP; an in-depth evaluation of the seismic hazard and risk at the plant), the 1993 EPRI study of EUS ground motions, the 1995 Southern California Earthquake Center study of scenario earthquakes in southern California, the 1996 Yucca Mountain (Nevada) study of scenario earthquakes, and the 1997 Yucca Mountain probabilistic seismic hazard analysis. The NCEER/FHWA workshop was constructed using what was learned from these studies in terms of how to organize the exercises (necessary constraints), how to validate the models, and how to compare the results. Several participants in the workshop also contributed to one or more of the previous studies.

The validation is intended to evaluate how well the models can predict ground motion from a past earthquake. Each modeler estimates ground motion for a recorded earthquake using source, path, and site parameters that are appropriate for the events and optimizing other model parameters to provide the best data fit. Comparisons of the predicted ground motions with the recorded motions results in model misfits to the data, an important element of the uncertainty in future estimates of ground motion in postulated earthquakes. Although comparisons against recordings from more than one earthquakes is needed to validate a model, a single earthquake validation exercise was performed in this workshop to demonstrate the concept and to provide a rough evaluation of the adequacy of the models.

In the simulation exercise, the numerical models are used to predict ground motion for a future earthquake. Select parameters (such as event magnitude, fault geometry, station locations, site or path parameters) are fixed and multiple realizations are performed which randomize event-specific parameters, which were optimized in the validation exercise. The predicted ground motions from the alternative modeling methods are summarized by the median ground motion and standard deviation (variability)

1.3 Treatment of Variability

The modeling methods used by the different groups include different sets of source, path, and site parameters. To track the variability of the model prediction, each model parameter must be declared as "fixed" or "event-specific." Event-specific parameters are optimized to the best value for each past earthquake considered in the validation exercise. Since the event-specific parameters are unknown for future earthquakes, they must be randomized in the scenario simulations. Fixed model parameters are not randomized in the scenario simulations because the effect of the variability of these parameters is captured in the misfits to the recorded data in the validation exercise (assuming enough earthquakes are included in the validation to represent the variability).

For example, one model may assume that the stress-parameter of the sub-events are constant for all earthquakes, whereas another model may assume that the stress-parameter is event-specific. The first model may accurately predict the median ground motion from a suite of past earthquakes (e.g., it is unbiased) but it will probably have a poorer fit to the individual earthquake than the second model. When predicting ground motions for a future earthquake, the first model would keep the sub-event stress-parameter fixed, but the second model would have to specify a distribution of the stress-parameter and then sample the distribution for a suite of simulations.

This leads to two types of variability of the predicted ground motions. The variability from the misfit of the predicted ground motions to recorded ground motions from past earthquakes is called "modeling variability." The modeling variability reflects the limitations of the model to predict the ground motion even when all of the event-specific parameters are known. In the context of the model, these variations are unexplainable randomness. The modeling variability can only be computed by comparing predicted ground motions to observed ground motions.

The variability due to variations in event-specific parameters for future earthquakes is called "parametric variability." This represents the variability of the ground motion that results from varying the event-specific source parameters. In contrast to the modeling variability, this source of variability is understood. The parametric variability is computed using multiple realizations of the simulation process that sample the range of event-specific parameters.

To compare the variability of ground motion predictions from alternative models, it is important to keep track of both the modeling variability and the parametric variability. The total variability is the combination of the modeling and parametric variability. In general, as more event-specific parameters are included in the model, the modeling variability is shifted to parametric variability. Whether the total variability goes up or down as more event-specific parameters are included depends on how well the distribution of the event-specific parameters for the events used in the validation agrees with the distribution assumed for those parameters in the simulations. If a large enough sample of events is used in the validation, then the total variability is unlikely to change as more event-specific parameters are used: the reduction in the modeling variability is offset by a corresponding increase in the parametric variability. There is, however, an advantage to shifting modeling variability to parametric variability: the cause of the parametric variability is understood; whereas, the cause of the modeling variability is not explicitly understood.

The validation has two purposes. First, it is intended to determine if the model predictions are unbiased on average. Second, it provides an estimate of the modeling variability.

In this workshop, we have only used a single event in the validation exercise. A single event is not sufficient to evaluate the model bias on average, nor does it provide an accurate estimate of the modeling variability. A full validation was beyond the scope of the workshop. Some of the models have been validated for a larger number of events in previous studies. When available, we have included these more comprehensive validation results in these proceedings in addition to the single event validation results.

1.4 Treatment of Uncertainty

The variability discussed above is called "aleatory" variability. It represents variability that is considered to be random. In addition to aleatory variability, there is "epistemic" uncertainty. Epistemic uncertainty is uncertainty due to insufficient data (lack of information). In ground motion modeling, epistemic uncertainty results from uncertainty in the distributions of parameter values.

For a fixed model parameter, there is epistemic uncertainty on the best fixed value due to the small number of earthquakes used in the validation. For an event-specific model parameter, there is epistemic uncertainty in the probability density function for the parameter. Using the example of sub-event stress parameter again, if it is a fixed parameter, there is epistemic uncertainty in the best average value due to the small number of earthquakes used in the validation. If it is an event-specific parameter, then there is uncertainty both in the median value and standard deviation used to represent the range of sub-event stress parameter values for future earthquakes.

In previous studies, epistemic uncertainty has not typically been assessed for individual models, but rather it has been assessed by comparing the median and variability of ground motions from alternative credible models. (Here, credible implies that the model has an acceptably small model bias in the model validation.) This approach also incorporates the uncertainty in the basic underlying physical model used in the numerical process.

Because epistemic uncertainty is due to lack of data, as more data become available, epistemic uncertainty will be reduced. The additional data will provide constraints on the distribution of event-specific parameters and the alternative modeling methods should produce more similar results as they are modified based on additional earthquake recordings

SECTION 2
GROUND MOTION MODELING METHODS

Nine scientists experienced in ground motion modeling were invited to participate in the workshop. They were asked to both validate their models and estimate motions for the earthquake scenario. As part of the exercise, both median values and the variabilities in ground motions were to be estimated. Several of the simulation methods considered here have previously been used to obtain ground motions for engineering projects. These typically have been calibrated against recordings from a number of eastern and/or western U.S. events. Other participants' methods are more experimental in nature and have not yet been calibrated against a large number of past earthquakes.

2.1 Selection of Modeling Methods

A set of criteria was developed to aid in the selection of modeling methods and participating modelers. The criteria included:

- The methods are amenable to evaluation of parameter sensitivity and ground motion uncertainty.
- The methods are appropriate for application in the EUS.
- The modelers are experienced in the field.
- The modelers are familiar with ground motion modeling for engineering purposes.

When possible, modelers who had previously applied their models on MCEER projects were given preference in the selection process.

Of the range of modeling approaches available for application, nine individuals familiar with various methods were asked to participate. The nine selected and the methods they applied were:

- John Anderson (Univ. Nevada, Reno) - Composite Fractal Source Method
- Gail Atkinson (Carleton Univ.) - Stochastic Model with Empirical Source Spectrum
- Shyh-Jeng Chiou (Geomatrix Consultants) Hybrid Kinematic Source Model
- Steve Horton (Lamont-Doherty Geological Observatory)
- Larry Hutchings (Lawrence Livermore National Laboratory) - Empirical and Analytical Green's Function Method
- Dan O'Connell (Bureau of Reclamation) - Isochron Method
- Apostolos Papageorgiou (Rensselaer Polytechnic Inst.) - Specific Barrier Method
- Walt Silva (Pacific Engineering & Analyses) - Stochastic Method with ω^2 Sub-events
- Paul Somerville (Woodward-Clyde Federal Services) - Broadband Green's Function Method

Ultimately, eight of the invited participants contributed in some manner to the study (all excepting Dr. Horton). The eight simulation methods are described in the following section. Three participants limited their participation to a varying extent: Dr. Hutchings performed the validation exercise only; Dr. Papageorgiou briefed the other participants on his modeling method and did not contribute to the validation or scenario exercises; Dr. Somerville did not perform the validation exercise as his model had previously been calibrated against the Saguenay event.

2.2 Description of Simulation Methods

All the various modeling methods applied may be considered as 'physically-based' in that they are based on seismological models of the source, wave propagation, and site effects. All of the models used a finite-source in which the motions for the desired event are formed by summing the ground motions from a number of smaller sub-events distributed on a rupture plane. Taken together, the models represent a broad range of technical approaches to simulating ground motions. The inherent assumptions (and the models) of the sub-events and the manner in which the sub-events combine to build the mainshock differ in each model. They differ in the manner in which seismic slip is distributed and released on the fault surface, in their assumptions of wave propagation, in their assumptions of site response, and in their overall level of complexity. Nevertheless, they accommodate the essential aspects of seismic energy being generated by a finite source and propagated along a path to a recording site. The simulation methods are briefly discussed below.

2.2.1 Composite Fractal Source Method

Dr. John Anderson and Shen-Der Ni apply the composite source model. The source model was developed by Zeng et al. (1994) and comprises a superposition of circular sub-events across a fault area, with the sub-event radii distributed according to a power law (Frankel, 1991). The sub-events are modeled as Brune pulses (ω^{-2} spectra roll-off). The stress drop of the sub-events is constant over the fault plane except at shallow depths, where it decreases to zero.

Wave propagation is accommodated using synthetic Green functions generated from the generalized reflection and transmission coefficients method for a layered earth (Luco and Apsel, 1983) and wave scattering based on isotropic scattering theory. The site response may be modeled either by a kappa filter with crustal factors (Su et al., 1996) or by a site-specific velocity profile with Q; the former was used in this study.

2.2.2 Stochastic Model with Empirical Source Spectrum

A stochastic finite-fault model was applied by Drs. Gail Atkinson and Igor Beresnev (Beresnev and Atkinson, 1997, 1998a). A rectangular fault plane is assumed. The rupture initiates at the hypocenter and propagates radially from it. The velocity of rupture propagation is assumed to equal 0.8 times the shear wave velocity. The fault plane is subdivided into rectangular elements (sub-faults); each sub-fault is triggered as the rupture reaches its center. The number of sub-fault triggerings is adjusted to conserve the total moment of the modeled earthquake. Inhomogeneous slip distribution on the target fault is allowed. The sub-fault acceleration time histories are propagated to the observation point using empirical distance-dependent duration, geometric attenuation, and attenuation (Q) models. The "kappa" high-cut filter is applied. The total radiated field is obtained by summing contributions from all sub-faults.

The source spectrum for each sub-fault is obtained by multiplying the ω^2 spectral shape by the normalized spectrum of a limited-duration Gaussian noise. The corner frequency of the ω^2 spectrum and the sub-fault moment are derived from the sub-fault size. The amplitude of high frequency radiation is controlled by the radiation-strength factor, which is proportional to the maximum slip velocity on the fault. The frequencies modeled are 0.1 to 50 Hz.

2.2.3 Hybrid Kinematic Source Model

Dr. Chiou's simulation procedure uses a hybrid source model and broadband Green's functions for a layered crust. The source model is a hybrid model in the sense that the slip amplitude at small wavenumber follows a pre-specified spatial distribution, while at large wavenumber it follows a power law decay of κ^2 (κ is the wavenumber) (Herrero and Bernard, 1994; Joyner, 1995) with a randomly assigned phase. For example, in the validation exercise, the Saguenay source is represented as the superposition of a stochastic slip distribution on top of the smoothly varying slip distribution obtained by modeling the recorded strong motion records (Hartzell and others, 1994).

Following Bernard et al. (1996), the source time function has a scale-dependent rise time that corresponds to a propagating source pulse with a finite spatial width. Furthermore, a scale-dependent rake angle is also adopted so that the angle of the large wavenumber slip component is randomized, while the angle of the small wavenumber slip component follows a specified value (78° for the Saguenay earthquake and 90° for the simulation exercise).

The theoretical Green's function is computed up to 30 Hz by the method of generalized reflectivity (Luco and Apsel, 1983; Zeng and Anderson, 1994). Random rake angle and isotropic wave scattering are also included in the simulation to enhance the motions on the near nodal components (Zeng et al., 1995).

2.2.4 Empirical and Analytical Green's Function Method

Dr. Lawrence Hutchings, together with Dr. Steven Jarpe, has developed an exact solution to the representation relation for finite rupture that utilizes either empirical or synthetic Green's functions (Hutchings and Wu, 1990; Hutchings 1991, 1994; Jarpe and Kasameyer, 1996). In the MCEER study, recordings of small earthquakes are used as empirical Green's functions for frequencies of 0.5 to 25.0 Hz and analytical calculations are used to provide synthetic Green's functions for frequencies between 0.05 and 0.5 Hz. The entire wavetrain is synthesized for three components. Linear ground motions were developed as may be expected at the modeled rock outcrops.

The Kostrov slip rupture model with healing discussed by Hutchings (1991, 1994) is used for finite rupture. This results in a continuous rupture over fault segments with variable slip amplitude, but constant stress drop. A percentage of roughness can be added to the model that results in portions of high stress drop, and large asperities can be included that have relatively high stress drop. The rupture model includes rupture over the entire portion of the segment with higher slip amplitudes occurring within asperities.

In the study, empirical Green's functions were not available from the sites to be modeled, or along the source to be modeled. Instead, recordings from small earthquakes obtained at nearby weak-motions recorders were used to obtain empirical Green's functions. These were interpolated to have been located from the sites used in the modeling.

2.2.5 Isochron Integration with Empirical Scattering Functions

The isochron method was used by Dr. Dan O'Connell. The kinematic model consists of self-similar effective stresses with high effective-stress circular asperities imbedded in a fault with randomized rupture and healing velocities. Variable effective-stress asperities provide the dominant short period component of seismic energy. On the modeled surface, perimeter transition regions smoothly decrease effective stresses from the asperity interiors to fault background regions and also allow for abrupt changes in local rupture and healing velocities. Rupture and healing velocities and effective stresses are independently specified for asperity interiors. Asperities are allowed to heal from their transition regions inward.

Background regions of the fault that are far from healing boundaries (fault edges) are permitted to have substantially longer rise times than in the fault interior. This allows for quite heterogeneous distributions of rise time on the fault, consistent with the results of Mikumo and Miyatake (1987, 1993) and Fukuyama and Mikumo (1993). Short rise times in the asperities provide large amplitude short period radiation consistent with Heaton's (1990) observation of relatively short rise times for rupture models of large earthquakes. Longer rise times in the lower effective stress background region provide sufficient additional seismic moment to produce total moments consistent with observed broadband magnitudes (Horton, 1996). If short rise times are assumed everywhere on a fault, then the asperities are required to provide most of the moment and estimated effective stresses are extremely high. The variable rise-time parameterization provides a means to explain low and high frequency observations of large earthquakes, but requires less extreme effective stresses in the asperities than the constant rise time model.

Isochron integration was used to calculate synthetic seismograms by assuming that all significant radiation from the fault consists of first S-wave arrivals and that all seismic radiation from a fault can be described with rupture and healing isochrons. Nine microearthquakes, recorded in the Transverse Ranges of southern California, were used to derive site-specific scattering functions solely from the observed waveforms. Wave-shaping filters, W, were calculated (Yilmaz, 1987) to annihilate 2.5 sec to 3 sec waveform windows that immediately follow the first one to two cycles of the direct S-waves. The site-specific scattering function, *S*, is the inverse of *W*. To approximate the complexity of observed microearthquake waveforms noted in southern California, one of the nine scattering functions was selected at random at each integration position along an isochron and the appropriate radiation pattern, free-surface correction, geometric spreading, and take-off angle were applied to produce a band-limited site-specific Green function. Calculations were limited to a maximum frequency of 10 Hz.

2.2.6 Specific Barrier Method

The specific barrier method is followed by Dr. Apostolos Papageorgiou. The first step in strong motion prediction for a tectonic region like the eastern U.S., with an extremely limited recorded strong motion database, is to propose a physical model which, when calibrated against the very limited available data, would allow one to extrapolate from moderate events (such as the Saguenay earthquake) to large events (such as the scenario event). In other words, it is necessary to establish scaling laws for the various source parameters, based on the proposed model, so that one can predict/model the motion of large events for which there are no data.

The specific barrier model provides a complete framework for strong motion prediction, including scaling of source parameters, that may be used to specify realistic slip distributions on the fault plane (e.g., using the spectral representation technique of Shinozuka), as well as source spectra and their scaling law. Furthermore, the framework of the specific barrier model is very versatile, allowing one to predict strong ground motion using the engineering (stochastic) approach (e.g., a la Boore, 1983), or the seismological (kinematic modeling) approach using synthetic Green functions (e.g., a la Zeng et al., 1994), or a hybrid of empirical and synthetic Green functions (e.g., a la Somerville, 1993).

Dr. Papageorgiou uses the model of a circular crack to represent sub-events in the specific barrier model. The model is optimized by using two stress drops: a global value for the rupture as a whole and a local value for the sub-event. The source model superposes point sources positioned at the centroids of the isochron patterns for each recording site. Effectively, this assumes that the barrier crack boundaries are approximated by the isochrons and it ultimately represents an optimization of the hypocenter locations.

2.2.7 Stochastic Method with ω^2 Sub-events

The stochastic finite-fault method with ω^2 sub-events is practiced by Dr. Walt Silva of Pacific Engineering & Analysis. The method is an extension of the point-source stochastic method to the finite-fault case using the band-limited white noise (BLWN) model with random vibration theory (RVT).

The fault rupture plane is discretized into a number of equal size sub-fault regions. The radiation pattern is described by a constant, which is the average factor for all of the sub-fault regions. Different values of the slip are assigned to each sub-fault element to incorporate asperities into the model. Empirical models are used to estimate the rise times of the mainshock and sub-events. Heterogeneity of the source process is accommodated by randomizing the location of the sub-events within each sub-fault element and by randomizing the sub-event rise time.

The path effect is approximated using Q(f) and geometrical attenuation computed by raytracing from each sub-fault to the site. The crustal amplification is computed from the EPRI mid-continent model. Site effects are modeled by a kappa filter and an equivalent-linear model is incorporated into the finite-fault code to accommodate nonlinear site response (Silva and Lee, 1987).

RVT is used to estimate the response spectra to yield more stable estimates of the spectral values than the set of time histories provides. To generate time histories, the Fourier phase spectrum of the sub-event is represented empirically using a small (M 5.0) Eastern North America event recorded at a rock site at a close distance. The sub-event time history is estimated using the empirical phase with the ω^2 amplitude spectrum for the particular sub-event. This is then convolved with a spike seismogram developed from the rupture times and amplitudes of each sub-event. All validations have been done accommodating site conditions using generic rock or soil profiles and equivalent linear soil response.

2.2.8 Broadband Green's Function Method

The broadband Green's function is practiced by Dr. Paul Somerville of Woodward-Clyde Federal Services. This method combines two different procedures for the low frequency (less than 1 Hz) and high frequency (greater than 1 Hz) portions of the ground motion. At low frequency, theoretical source models are used including the theoretical radiation pattern; at high frequencies, empirical source functions are used that incorporate the radiation pattern empirically.

For both procedures, the fault rupture plane is discretized into a number of equal size sub-fault regions. Different values of the slip are assigned to each sub-fault element to incorporate asperities in the model. Empirical models are used to estimate the rise time of the mainshock. The sub-event rise time of the event from which the empirical source functions are derived is estimated independently. Heterogeneity of the source process is modeled by randomizing the selection of the empirical source functions and by randomizing the location of the sub-events within each sub-fault element.

Wave propagation is accommodated using synthetic Green's functions generated using the frequency-wavenumber integration for the long-period procedure and using generalized rays (direct and first multiple) for the high-frequency procedure. Linear site response is incorporated in the empirical source functions which have been corrected as necessary for eastern U.S. site kappa.

Table 2-1: Summary of Modeling Approaches

Participant	Source Model	Path Effect	Scattering	Site Effect
Anderson/Ni	• Composite finite model; superposition of circular sub-events with fractal distribution	• 1-D Green functions • Scattering	• Model parameter	• Kappa
Atkinson/ Beresnev	• Finite discretized into sub-faults • Inhomogeneous slip distribution • Sub-faults have stochastic ω^2 spectrum • Constant rupture velocity, randomized rise time, average radiation pattern	• Empirical EUS geometric spreading and Q models	• Empirical EUS distance-dependent duration model	• Kappa and any user-defined response function
Chiou	Kinematic finite source: • Self-similar spatial distribution of slip • Scale-dependent rise time	• Complete Green's function for a layered crust.	• Model parameter	• Kappa
Hutchings/ Jarpe	• Kinematic rupture; parameters are geometry, hypocenter, rupture velocity, healing velocity (rise time), and roughness	• Inherent in selected empirical EUS Green's functions	• Inherent in selected empirical EUS Green's functions	• Inherent in selected empirical EUS Green's functions
O'Connell	• Finite with a semi-fractal slip velocity distribution • Variable rupture and healing velocities • Self-healing high-stress-drop asperities • Variable rise time and radiation pattern	• 1/R geometric spreading with isochrons	• Empirical WUS scattering functions	• Included in empirical WUS scattering functions
Papageorgiou	• Finite specific barriers; model of circular crack used to represent sub-events • Sub-event stress drop (local stress drop) • fmax	• Green's function	• Scattered wave energy (Zeng et al., 1991 or Sato, 1989 models)	• From variations of velocity in the upper km of crust
Silva	• Finite Brune sub-event • Finite slip distribution from f-k model • Constant rupture velocity, randomized rise time, rake, average radiation pattern	• Either 1/R geometrical spreading or • 1-D or 2-D ray trace	• Empirical EUS model	• Kappa/equivalent linear for nonlinear site-specific response
Somerville	• Finite with slip distribution from f-k model • Variable rake, rise time, radiation pattern • Low f: continuous slip function with theoretical radiation pattern • High f: discretized grid with empirical source functions, corrected to the source	• Low f: Green functions from f-k integration, complete response and Q for layered medium • High f: simplified Green functions from G-R theory, dominant rays and Q for layered medium • 2- and 3-D modeled with G-R for high f and finite difference for low f	• Empirical WUS model	• Inherent in selected empirical source functions, corrected for kappa