

## EFFECTS OF CORRELATION OF SOURCE PARAMETERS ON GROUND MOTION ESTIMATES

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### ABSTRACT

Estimates of broadband ground motion from scenario earthquakes from kinematic models requires specifying the correlation between the source parameters. Most often, the correlation is assumed to be zero. However, there are hints from inversions of strong motion data and from dynamic models of spontaneously propagating shear fractures that the kinematic parameters are correlated. The correlation can affect the ground motion especially if the slip and rupture velocity are strongly correlated. The rupture velocity is critical in describing the source process. Inhomogeneities in the average rupture velocity have a strong influence on the development of the near source directivity pulse as well as the generation of high frequencies. Additional complications arise from ruptures that travel with supershear velocity. To investigate the influence of a correlation between slip and rupture velocity—both subshear and supershear, we use a new method (Liu et al., 2006) that is the first to account for correlations between source parameters. In this method the slip wavenumber distribution is a spatial random field; the slip amplitudes follow a truncated Cauchy distribution. The rise times follow a beta distribution and the average rupture velocity between the hypocenter and a point on the fault is uniformly distributed. We construct a kinematic model where the average rupture velocity on the fault is spatially correlated with the slip amplitude; similarly the rise time is spatially correlated with the slip amplitude. We show an example where the average rupture velocity is supershear, which produces a pattern of ground motion much different from subshear.

Keywords: earthquake source, ground motion, rupture velocity, supershear

### INTRODUCTION

Prediction of realistic time history of ground motion from future earthquakes is essential to completely describe earthquake hazard. While we cannot know the exact time of the next damaging earthquake, geologists, seismologists and geodesists have delineated faults that are capable of producing large magnitude earthquakes in urban areas. To reduce the hazard we discuss predictions for a range of broadband strong ground motion that capture the effects of *i*) a rupture on a finite fault, *ii*) the complexity of the three dimensional Earth model and *iii*) local site conditions.

A credible model of the complex source process is essential for the prediction of ground motion. Although efforts have been made to implement the dynamic modeling of extended source models to predict ground motions (Guatteri, *et al.*, 2003), high-frequency dynamic fault models are still quite difficult and computationally expensive. Although the computational limits can be overcome to some degree, these models will be restricted to low frequencies (less than 2-3Hz). Kinematic modeling remains as one of the best approaches to incorporate many aspects of physical models of the earthquake process while still being able to compute broadband strong ground motion. We have

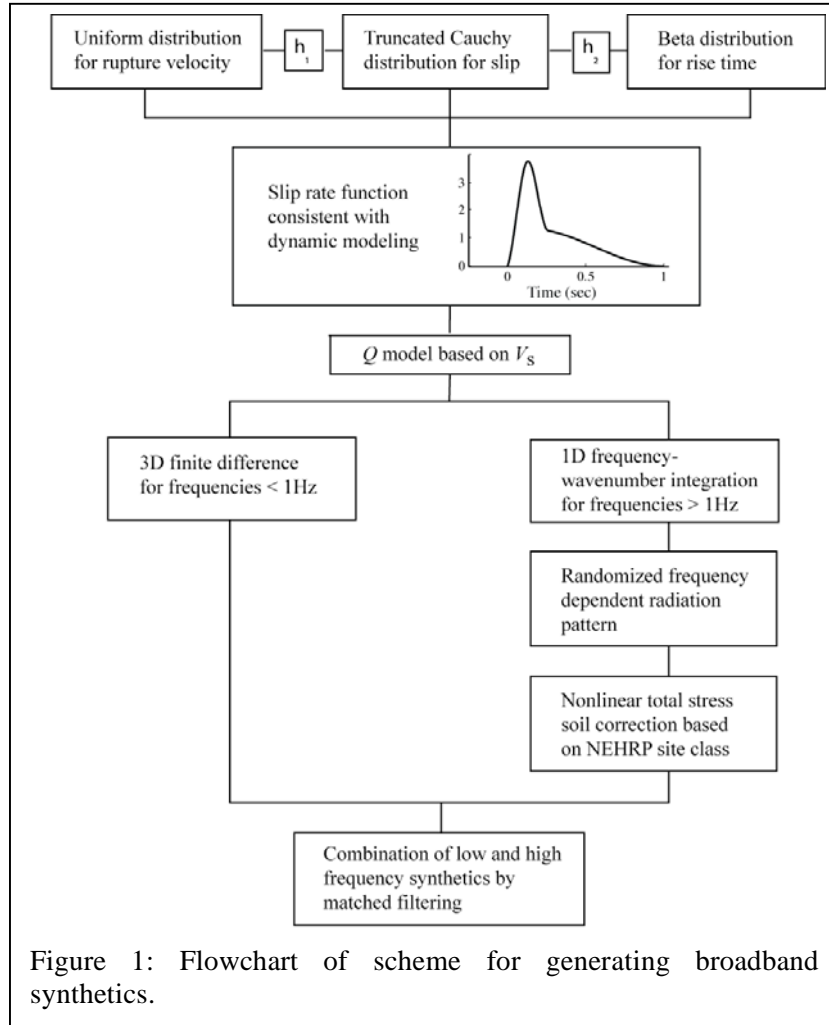
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developed a technique for kinematic modeling of an extended earthquake source that is based on distribution functions for the slip amplitude, duration of slip (rise time) and rupture time (Liu et al., 2006). The complexity of the source process is represented by spatial distributions of randomized source parameters, but the integrated characteristics of these parameters will be constrained by the total moment (magnitude), radiated energy and the high-frequency decay of the spectral amplitudes in the source spectrum.



We will use the kinematic source model and a three-dimensional Earth model to calculate synthetic ground motions for frequencies up to one to two Hertz. The 3D model incorporates the geometry of the geology in the area, including the deep basin structures. We also compute ground motions with the frequency up to 15-20 Hz using a 1D model where the travel times are consistent with the 3D model. Because strong ground motions, especially the high-frequency ground motion, can induce non-linear soil response near the surface, we first deconvolve the 1D ground motion to the bedrock level using the available geotechnical information. This bedrock time history is propagated to the surface using a 1D nonlinear wave propagation code (e.g., Bonilla *et al.*, 1998; Hartzell *et al.*, 2004). The 3D ground motions

(low-frequency) and high-frequency components of 1D synthetics (with consideration of nonlinear effects) are stitched together to form a broadband time histories of ground motion (Figure 1).

## STATISTICALLY DEFINED, CORRELATED KINEMATIC PARAMETERS

In contrast to the pseudo-dynamic source model description of Guatteri et al (2003), which utilizes the fracture energy to derive the rupture velocity, the average rupture velocity is directly correlated with slip on the fault in our approach (Liu et al., 2006). Hence the used kinematic source description is based on correlated random distributions for the slip amplitude, the average rupture velocity, and the rise time on the fault. It allows for the specification of source parameters independent of any a priori inversion results. The wavenumber distribution of the slip on the fault is based on the work of Mai and Beroza (2002). The slip amplitudes follow a truncated Cauchy distribution (Lavallée & Archuleta, 2003). Using a NORmal To Anything (NORTA) method (Cario and Nelson, 1997) it is possible to construct

- the average rupture velocity on the fault as a random field that follows a uniform distribution and that is spatially correlated (30 %) with the slip amplitude on the fault

- the rise time on the fault as a random field that follows a beta distribution and that is spatially correlated (60 %) with the slip amplitude on the fault

For given slip amplitudes and rise time we construct a slip rate function consistent with dynamic modeling Liu et al (2006).

The high frequency Greens functions are computed using the frequency wavenumber method (Zhu & Rivera, 2001). To get the high frequency synthetics for a given station we use a standard representation theorem that convolves the spatial varying slip rate function on the fault with the computed Greens functions and integrates this combination over the fault. To account for the effect of scattering on the high frequency radiation pattern, a frequency-dependent perturbation of azimuth, dip and rake of each subfault is implemented similar to Pitarka et al. (2001). Rather than randomizing the strike, which tends to be quite stable over tens of kilometers, we randomize the azimuth at which waves approach a station. Nonlinear site effects are then incorporated into the 1D ground motions based on the site category (e.g., Bonilla *et al.*, 1998; Hartzell *et al.*, 2004). We use a three-dimensional (3D) Earth model to calculate synthetic ground motions for frequencies up to one to two Hertz. Finally the 3D ground motion (low-frequency) and high—frequency components of 1D synthetics are stitched together to form a broadband time histories of ground motions. At present we choose a crossover frequency at 1 Hz. With better 3D structure and with our improved FD code, we can efficiently simulate low-frequency wave propagation in a 3D structure up to 2Hz. A detailed description of this approach can be found in Liu et al. (2006).

To simulate stochastically the kinematic faulting process we divide the fault of the mainshock into subevents. For each subevent we prescribe the slip history. In our model each subevent represents a point source with parameters consisting of the local slip amplitude, rupture velocity, and rise time—all of which are poorly constrained for future earthquakes. In order to allow for our inadequate *a priori* knowledge we describe these parameters as random variables with probability distribution functions that are bound by estimates of the parameters based on past earthquakes.

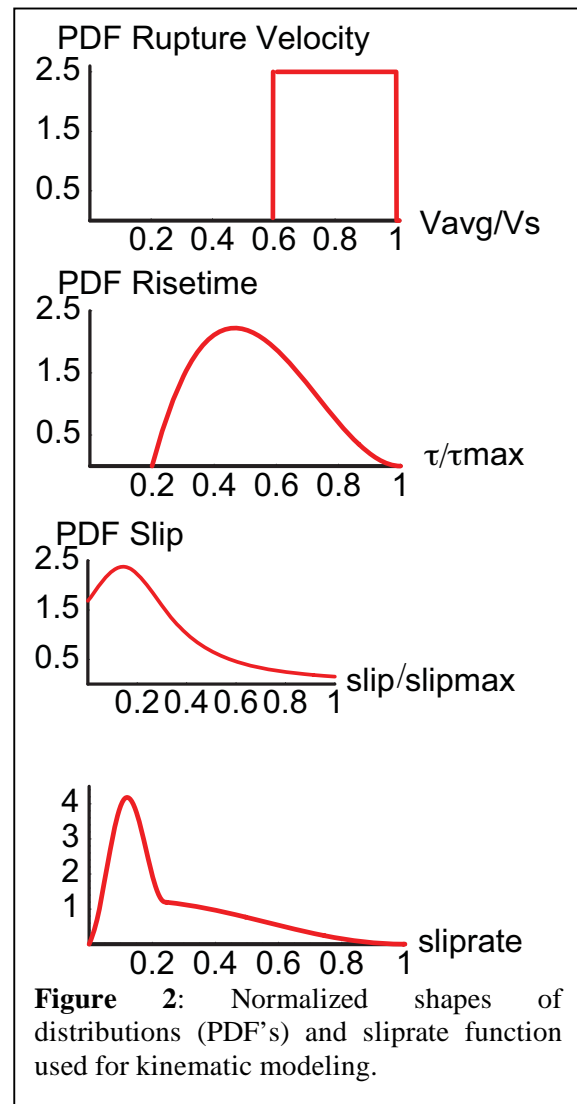
The stochastic distribution of a source parameter (slip amplitude, risetime, or rupture velocity) is constructed by filtering a white noise using a  $k^{-2}$  decay filter in the two-dimensional wavenumber domain. The filter has the form (Mai and Beroza, 2002):

$$F(k_x, k_y) = \left\{ 1 + \left[ (k_x C_L)^2 + (k_y C_W)^2 \right] \right\}^{-1}, \quad (1)$$

where  $C_L$  and  $C_W$  are correlation lengths along strike and dip, respectively. They are calculated using the empirical relations obtained by Mai and Beroza (2002):

$$\begin{aligned} \log_{10}(C_L) &= -2.5 + M_w / 2, \\ \text{and } \log_{10}(C_W) &= -1.5 + M_w / 3. \end{aligned} \quad (2)$$

The white noise for slip amplitudes is generated by



a truncated Cauchy probability distribution (Lavallée and Archuleta, 2003):

$$p(D) = C \frac{1}{1 + [(D - D_0)/\kappa]^2}, \quad 0 \leq D \leq D_{\max} \quad (3)$$

with the constraint: the maximum slip of the target event  $D_{\max} = 3.5 \bar{D}$ ;  $C$  is a normalizing factor. The factor  $\kappa$  is determined such that the generated random variables have a mean value of  $\bar{D}$ . We adjust  $D_0$  to match the energy radiated from our kinematic source model with the radiated energy of the mainshock. We use Brune's  $\omega^{-2}$  source spectrum (Brune, 1970) to calculate the energy radiated from a large event. Given the rupture velocity, risetime, and slip-rate function defined below, we find that  $D_0 \approx 0.5 \bar{D}$ .

We chose the probability distribution of rupture velocity and risetime based on three observations: (i) the areas of large slips correlate with high rupture velocities; (ii) most finite fault inversions have found large slip located in a few small areas; and (iii) the average rupture velocity is around  $0.8V_s$ . To reflect these characteristics, we calculate the rupture velocities  $V_r$  using a uniform distribution between 0.6 and 1.0  $V_s$ . Dynamic modeling of complex rupture process shows that the areas of large slip correlate with fast rupture velocity. We assume that the correlation between secant (average between hypocenter and a point on the fault) rupture velocity (Day, 1982) and slip is about 30% and the correlation between rise-time and slip is 60%.

For the rise time we consider a Beta distribution:

$$p(\tau) = C (\tau - \tau_{\min})(\tau_{\max} - \tau)^2; \quad \tau_{\min} \leq \tau \leq \tau_{\max} \quad (4)$$

We assume  $\tau_{\max} = 5\tau_{\min}$  where  $\tau_{\max}$  is determined by matching the spectral levels at high frequency, basically infinity, in Brune's  $\omega^{-2}$  model.

The slip rate function (Figure 2, bottom plot) is a principal component in the prediction of broadband ground motion. Our slip rate function consists of sine and cosine functions. At high frequency its spectrum has  $\omega^{-2}$  decay. Moreover, both the first and second derivative of the slip rate function has a non-zero value at its starting time—the initial phase of the simulated rupture process will radiate high-frequency energy (see more discussion below). Also note that the slip rate function is not symmetric—characteristic of slip rate functions determined in dynamic simulations (e.g., Day, 1982; Andrews, 1976).

## VALIDATION AND VERIFICATION

We have validated the method using data from 30 stations that recorded the Northridge earthquake (Liu et al., 2006). The parametric uncertainty consists of the uncertainties in our input parameters: 1) seismic moment, corner frequency of the mainshock, geometry of the main fault (strike, dip, length, and width), and location of the hypocenter. Effects of the uncertainties in these parameters can be considered by performing several predictions separately using a wide range of values for these parameters.

The bias of the  $i^{th}$  estimated ground motion parameter derived from  $M$  simulations is given by:

$$\begin{aligned} B_i &= \frac{1}{M} \sum_k^M [\ln(S_{ik}) - \ln(O_i)] \\ &= \left[ \frac{1}{M} \sum_k^M \ln(S_{ik}) \right] - \ln(O_i) \end{aligned} \quad (5)$$

and the standard error of the estimate is given by

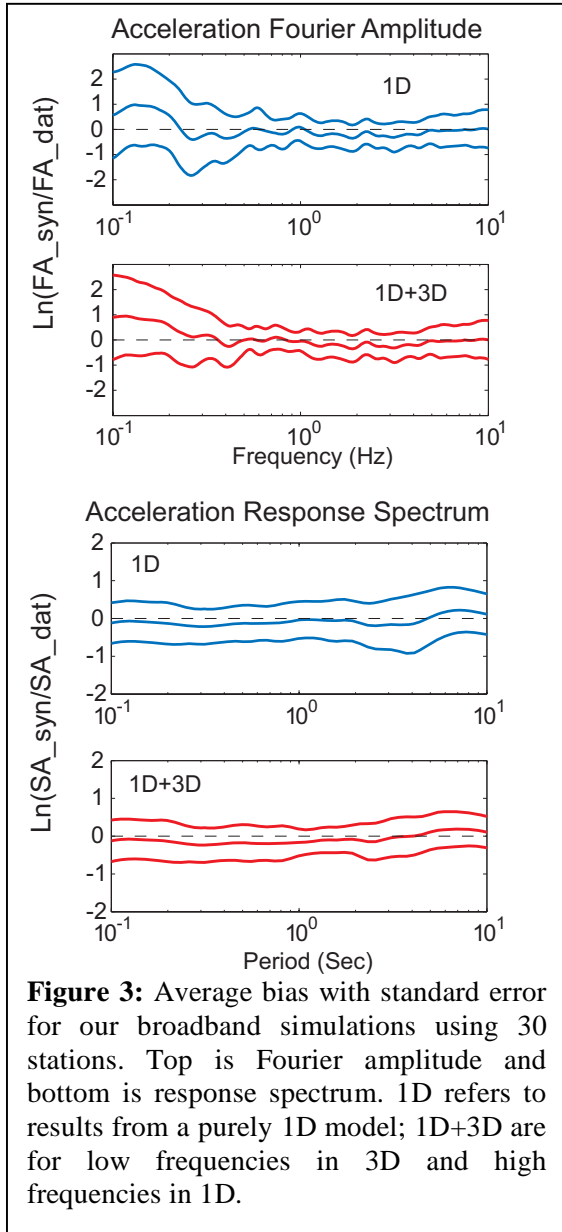
$$E_i = \sqrt{\frac{1}{M} \sum_k^M [(\ln(S_{ik}) - \ln(O_i)) - B_i]^2}$$

$$= \sqrt{\frac{1}{M} \sum_k^M [(\ln(S_{ik}))^2 - [\frac{1}{M} \sum_k^M \ln(S_{ik})]^2]}$$
(6)

(Abrahamson *et al.*, 1990, Schneider *et al.*, 1993). The average bias and standard error over  $N$  data are

$$\hat{B} = \frac{1}{N} \sum_i^N B_i \quad \text{and} \quad \hat{E} = \sqrt{\frac{1}{N} \sum_i^N E_i^2},$$
(7)

respectively. Combining  $\hat{B}$  and  $\hat{E}$  we have complete estimation of the modeling uncertainty in our method. The results for the Northridge validation are shown in Figure 3.

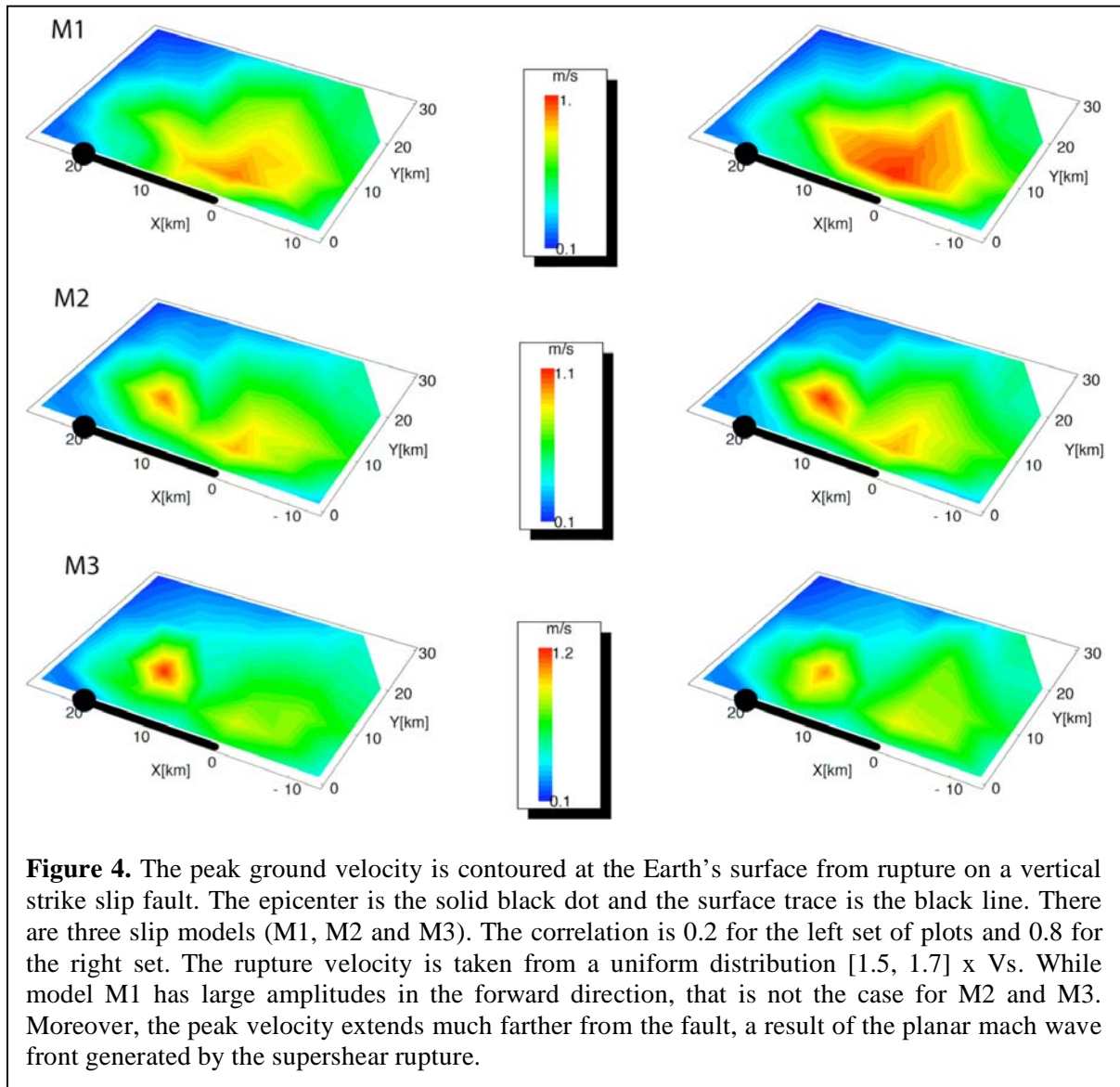


The salient points of our approach are: 1) the bias and error are as small if not smaller than other methods; 2) combining 1D and 3D reduces slightly the misfit at low frequencies (the large misfit below 0.2 Hz is because the data are filtered below 0.2 Hz); 3) the faulting model used to generate the broadband synthetics is not constrained by an a priori inversion result; 4) the modeling is independent of specific values for slip rate at a point on the fault.

## SUPERSHEAR RUPTURE

Earthquake scenarios using constant rupture velocity have generally been used to investigate the influence of rupture velocity on ground motion. Dunham and Archuleta (2005) computed near source ground motion from steady state rupture pulses for both subshear and supershear ruptures. For the supershear case they find a planar wavefront emanating from the fault and carrying an exact history of the slip rate on the fault. Because the wavefront is planar in the near field, there is no geometrical spreading to attenuate the amplitude of the ground motion as in the subshear case. (Aaagard and Heaton (2004) use a kinematic source model with constant subshear and supershear rupture velocities combined with finite element wave propagation to show that the pattern of observed ground motion changes when going to higher rupture velocities. Bernard and Baumont (2005) have also investigated the effect of constant supershear rupture on ground motion.

The classic effect of a subshear rupture is to increase the amplitude of the ground motion in the direction that the rupture propagates, i.e., directivity. This has a pronounced effect on the amplitude of the ground velocity near the fault (Archuleta and Hartzell, 1981; Archuleta, 1984; Hall et al., 1995). It is less clear how the ground motion will be affected when the rupture is on average supershear but variable. We have begun to investigate this problem using the simulation method outlined above. In Figure 4 we show three examples of the pattern of the surface ground velocity where the rupture has a supershear velocity. In these cases we have used taken the velocity from a uniform distribution between  $1.5\text{--}1.7 \times V_s$  where  $V_s$  is the shear wave speed of the medium and we have considered a two values of correlation, 0.2 and 0.8, between the rupture velocity and the slip.



The pattern of peak ground velocity (PGV) is quite different from subshear ruptures. The large amplitudes extend over a greater area far from the fault and are not only in the forward direction of the rupture, e.g., note model M3. Thus in cases where supershear ruptures are inferred for past earthquakes, e.g., 1979 Imperial Valley, California (Archuleta, 1984), 1999 Izmit, Turkey (Bouchon et al., 2000), 1999 Düzce, Turkey (Bouchon et al., 2001), 2002 Denali, Alaska, earthquake (Dunham and Archuleta, 2004; Ellsworth et al., 2004) and the 2001 Kunlun, Tibet (Bouchon and Vallée, one might expect stronger ground motion away from the fault than predicted by subshear ruptures.



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## REFERENCES

- Aagaard, B. T., and T. H. Heaton, (2004). Near-source ground motions from simulations of sustained intersonic and supersonic fault ruptures, *Bull. Seism. Soc. Am.*, **94**, 6, 2064-2078.
- Abrahamson, N., P. Somerville, and A. Cornell (1990). Uncertainty in numerical strong motion predictions, in *Proc. Of the Fourth U.S. National Conference on Earthquake Engineering*, Vol. 1, 407-416.
- Andrews, D. J. (1976). Rupture propagation with finite stress in antiplane strain, *J. Geophys. Res.* **81**, 3575-3582.
- Archuleta, R. J. (1984). A faulting model for the 1979 Imperial Valley earthquake, *J. Geophys. Res.*, **89**, 4559-4585.
- Archuleta, R. J., and S. H. Hartzell, (1981). Effects of fault finiteness on near-source ground motion, *Bull. Seism. Soc. Am.*, **71**, 939-957.
- Bernard, P., and D. Baumont, (2005). Shear mach wave characterization from kinematic fault rupture models with constant rupture velocity, *Geophys. J. Int.*, **162**, 431-447
- Bonilla, L., D. Lavallée, and R. Archuleta (1998). Nonlinear site response: Laboratory modeling as a constraint for modeling accelerograms, in *Proc. The Effects of Surface Geology on Seismic Motion*, Yokohama, Japan, **2**, 793-800.
- Bouchon, M., M. N. Toksöz, H. Karabulut, M. P. Bouin, M. Dietrich, M. Akatar and M. Edie, (2000). Seismic imaging of the Izmit rupture inferred from near-fault recordings, *Geophys. Res. Lett.*, **27**, 3013-3016.
- Bouchon, M., M. P. Bouin, H. Karabulut, M. N. Toksöz, M. Dietrich, A. J. Rosakis, (2001). How fast is rupture during an earthquake? New insights from the 1999 Turkey earthquakes, *Geophys. Res. Lett.*, **28**, 2723-2726.
- Bouchon, M. and M. Vallée (2003). Observation of long supershear rupture during the Magnitude 8.1 Kunlunshan earthquake, *Science*, **301**, 824-826.
- Brune, J. N. (1970). Tectonic stress and the spectra of seismic shear waves from earthquakes, *J. Geophys. Res.*, **76**, 5002.
- Cario, M.C. and B.L. Nelson (1997), Modeling and generation random vectors with arbitrary marginal distributions and correlation matrix. Tech Rep., *Department of Industrial Engineering and Management Sciences, Northwestern University, Evanston, Ill.*
- Day, S. M. (1982). Three-dimensional simulation of spontaneous rupture: the effect of non-uniform prestress, *Bull. Seism. Soc. Am.*, **72**, 1881-1902.
- Dunham, E.M., and R. J. Archuleta, (2004). Evidence for a supershear transient during the 2002 Denali Fault earthquake, *Bull. Seism. Soc. Am.*, **94**, S256-S268.
- Dunham, E.M., and R. J. Archuleta, (2005). Near-source ground motion from steady state dynamic rupture pulses, *Geophys. Res. Lett.*, **32**.
- Ellsworth, W. L., M. Celebi, J. R. Evans, E. G. Jensen, D. J. Nyman and P. Spudich (2004). Processing and modeling of the pump station 10 record from the November 3, 2002, Denali fault, Alaska earthquake, in *Proc. 11<sup>th</sup> Int. Conf. Soil Dynam. Earthq. Eng. 1*, Berkeley, CA, 471-477.
- Guatteri, M., P. Mai, G. Beroza, and J. Boatwright (2003). Strong ground-motion prediction from stochastic-dynamic source models, *Bull. Seism. Soc. Am.*, **93**, 301-313.
- Hall, J., T. Heaton, M. Halling, and D. Wald (1995). Near-source ground motion and its effects on flexible buildings, *Earthquake Spectra*, **11**, 569-605.
- Hartzell, S., L. F. Bonilla, and R. A. Williams (2004) Prediction of nonlinear soil effects, *Bull. Seism. Soc. Am.*, **94**, 1609-1629.

- Lavallée, D. and R. Archuleta (2003). Stochastic modeling of slip spatial complexities for the 1979 Imperial Valley, California, earthquake, *Geophys. Res. Lett.*, **30**, 1245, doi:10.1029/2002GL015839.
- Liu, P., R. J. Archuleta and S. H. Hartzell (2006), Prediction of broadband ground motion time histories: Hybrid low/high-frequency method with correlated random source parameters, *Bull. Seism. Soc. Am.* **96**, in press.
- Mai, P. M., and G. C. Beroza (2002). A spatial random field model to characterize complexity in earthquake slip, *J. Geophys. Res.* **107**, 1-21.
- Pitarka, A., P. Somerville, Y. Fukushima, T. Uetake, and K. Irikura (2000). Simulation of near-fault ground-motion using hybrid Green's functions, *Bull. Seism. Soc. Am.*, **90**, 566-586.
- Somerville, P., K. Irikura, R. Graves, S. Sawada, D. Wald, N. Abrahamson, Y. Iwasaki, T. Kagawa, N. Smith, and A. Kowada (1999). Characterizing crustal earthquake slip models for the prediction of strong motion, *Seism. Res. Lett.*, **70**, 59-80.
- Schneider, J., W. Silva, and C. Stark (1993). Ground motion model for the 1989 M 6.9 Loma Prieta earthquake including effects of source, path, and site, *Earthquake Spectra*, **9**, 251-287.
- Zhu, L. and L. Rivera (2001). Computation of dynamic and static displacement from a point source in multi-layered media, *Geophys. J. Int.*, **148**, 619-627.



