2009 SCEC ANNUAL REPORT:
PREDICTION OF BROADBAND TIME HISTORIES

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Abstract

By analysis of 315 dynamic rupture models we deduced the amplitude distributions and correlation of kinematic parameters. We construct probability density functions for the amplitude distributions and the correlation between source parameters. Limiting our analysis to subshear velocity, we find i) final slip does not correlate with the local rupture velocity; (ii) final slip correlates with rise time, (iii) rupture velocity correlates with peak slip rate; (iv) rupture velocity is controlled by both the fracture energy and the slope of the linear slip-weakening curve, (v) The crack length becomes more pulse-like with the distance from hypocenter. These new correlations have replaced those previously used in our method for constructing broadband time histories.

Method

Since the seminal papers by *Haskell* [*1964, 1969*], the kinematic model of an earthquake has been a standard approach for computing ground motion, especially for near-source strong motion. Besides the fault geometry, there are basic kinematic parameters —slip (slip rate) time function, final slip, and rupture velocity (or rupture time) —necessary to define the earthquake source. This kinematic model of an earthquake makes the strong assumption that we know *a priori* the spatio-temporal evolution of slip during the earthquake. Haskell's original models included no information about the correlation among the different parameters —a correlation that can certainly affect the resulting ground motion [*Schmedes, 2010*].

With more advanced computing power and better information on the nature of the friction law, ground motion can be computed from fully dynamic simulations based on the physics of the earthquake rupture process. While this is possible, it becomes computationally very expensive (prohibitive if there is no access to supercomputers) as one goes to frequencies of engineering interest, such as 10 Hz and to distances of 10s to 100s of kilometers in an earth structure where low velocity is near the surface.

The basic outline of our broadband simulations follows that of Liu et al. (2006) as shown in Figure 1. The difference is that we have changed the correlations based on what we have learned from earthquake simulations based on full dynamics with slip weakening friction. In our approach [*Schmedes et al., 2010*] we have used physics based simulations to determine the correlations among the kinematic parameters. Knowing these correlations we can then use the kinematic approach (Figure 1) to compute ground motions. Our approach is a synthesis of both dynamic and kinematic models in computing realistic ground motions from expected earthquakes.

To simulate physics-based earthquakes we use a structured mesh finite element code with one point integration and absorbing boundaries to compute dynamic ruptures for a strike slip fault in a 3D medium [*Ma and Liu*, 2006]. We computed ruptures for fault lengths between 30 km and 120 km, rupture widths between 12 km and 20 km, in three different 1D velocity structures: halfspace, layer over halfspace, and a 1D velocity gradient. We use a grid spacing 60 m in our computations, allowing a maximum frequency of 5.0 Hz. The friction is described by a linear slip weakening [*Ida, 1972*] or linear time weakening [*Andrews, 2004*]. The slip weakening distance is either constant or spatially heterogeneous. The normal stress is 100 MPa in most models; 14 ruptures have a depth dependent normal stress and stress drop. The dynamic coefficient of friction is a constant 0.5. Initial shear stress is spatially heterogeneous on the fault. The wavenumber power spectrum of initial shear stress is attenuated according to a power law with exponent *n* [*Lavallée et al.*, *2006*]. The power spectrum of is proportional to k^{-v}, where *k* is the 2D radial wavenumber. We use exponents *n*=1, 2, 3 and 4. The initial stress amplitude PDF distribution is Cauchy. The peak (yield) stress is constant or spatially varying —dependent on the initial stress.

We compute several kinematic parameters from the dynamic slip time history on the fault in order to analyze correlations among them. Because there is no re-strengthening in the slip weakening description for a large number of ruptures in the database, points on the fault can slip for a long time at low slip rates due to the lack of healing. In order to extract rise times T_r relevant for kinematic modeling, we fit a slip rate function $\dot{s}(t)$ that is constructed by convolving the slip rate function by Nielsen and Madariaga [2003] with a half sine of width T_p to the dynamically computed slip rate time series. This slip rate function is defined in Eq. (1) for $t \geq 0$. The function $H(t)$ is the Heaviside function, T_0 is the rupture time. The constant A is given by imposing the condition $\int_{-\infty}^{\infty} \dot{s}(t)dt = 1$.

$$\dot{s}(t) = \mathrm{A} \cdot \mathrm{Re}\left(\frac{\sqrt{T_0 + T_r - T_p - t}}{\sqrt{t - T_0}}\right) * H(T_p - t)\sin\left(\pi \frac{t}{T_p}\right) \qquad (1)$$

This formulation of the slip rate function is very similar to the formulation introduced in Tinti et al. [2005] and used in Tinti et al. [2009]. In these studies they use a triangle instead of a half sine. They show that the half-length of the triangular function, the equivalent of our parameter T_p, is linearly related to the time to reach the peak slip velocity (i.e. duration of positive slip acceleration). Hence the peak time T_p controls the duration of the impulsive part of the slip rate function.

From the dynamically computed slip rate we extract the peak slip rate $\dot{s}_{\max}$ and the final slip s_{total}. Because points on the fault can slip for a long time at low rates, we compute a slip s_{kin}, that is accumulated slip until the slip rate reaches zero for the first time. We compute the local rupture velocity v_r as the inverse of the norm of the numerical gradient of the rupture time [*Oglesby and Day*, 2002]. In order to get a smooth rupture velocity distribution we smooth the two directional derivatives using a mask with a dimension of 240 m x 240 m before we compute the inverse norm of the numerical gradient.

We computed the spatial correlation coefficients for different parameter pairs and 315 spontaneous rupture models, including three dynamic Shakeout ruptures computed by Dalguer (2008, pers. Comm.). Selected histograms of the correlations are shown in Figure 2. The first important result is contained in the first row, which shows the correlation of final slip with the ratio of rupture velocity over shear wave velocity. The distribution is centered on zero, hence for most ruptures there is no correlation between these two parameters—significantly different from the assumption of Liu et al. (2006). Therefore, for a given slip distribution on the fault there are many fundamentally different spatial distributions of rupture velocity possible, which translates into greater variability in the possible ground motion. This result argues against using slip as a controlling parameter for rupture velocity. If a positive correlation between slip and rupture velocity is assumed, areas of large slip are sampled in a shorter time (faster rupture), which yields strong peaks in the ground motion. Hence, if such a correlation is wrongly assumed one might over-predict ground motion.

However, total slip does show a positive correlation with rise time, that is, larger slip is obtained for longer rise times. The ratio of rupture velocity over shear wave velocity correlates positive with peak slip rate and negative with the duration of the peak in the slip rate function. That is, fast rupture velocities and short peak times accompany larger peak slip rate. Consistent with this picture is also the negative correlation between peak slip rate and peak time. The complete description of the newly found correlations is in the paper by Schmedes et al. (2010).

Following the framework of Liu et al. (2006) but using different correlations, our results suggest that a kinematic rupture model can be constructed using four parameters: s_{kin}, T_p, T_r, and γ where γ is the ratio of the rupture velocity to the local shear wave velocity. Liu et al. (2006) used only slip, rise time and secant velocity. In their model the duration of the acceleration phase is computed using $C \cdot T_r$ where C is a constant. One can use the correlations and create correlated stochastic fields by assuming the following chain: the slip controls the rise time, the rise time controls the peak time, and finally, the peak time controls the rupture velocity. This approach has been used incorporated into the platform for computing broadband synthetic time histories.

Publications:

Schmedes, J., R. J. Archuleta, and D. Lavallée (2010). Correlation of earthquake source parameters inferred from dynamic rupture simulations, *J. Geophys. Res.,* **115**, B03304, doi:10.1029/2009JB006689.

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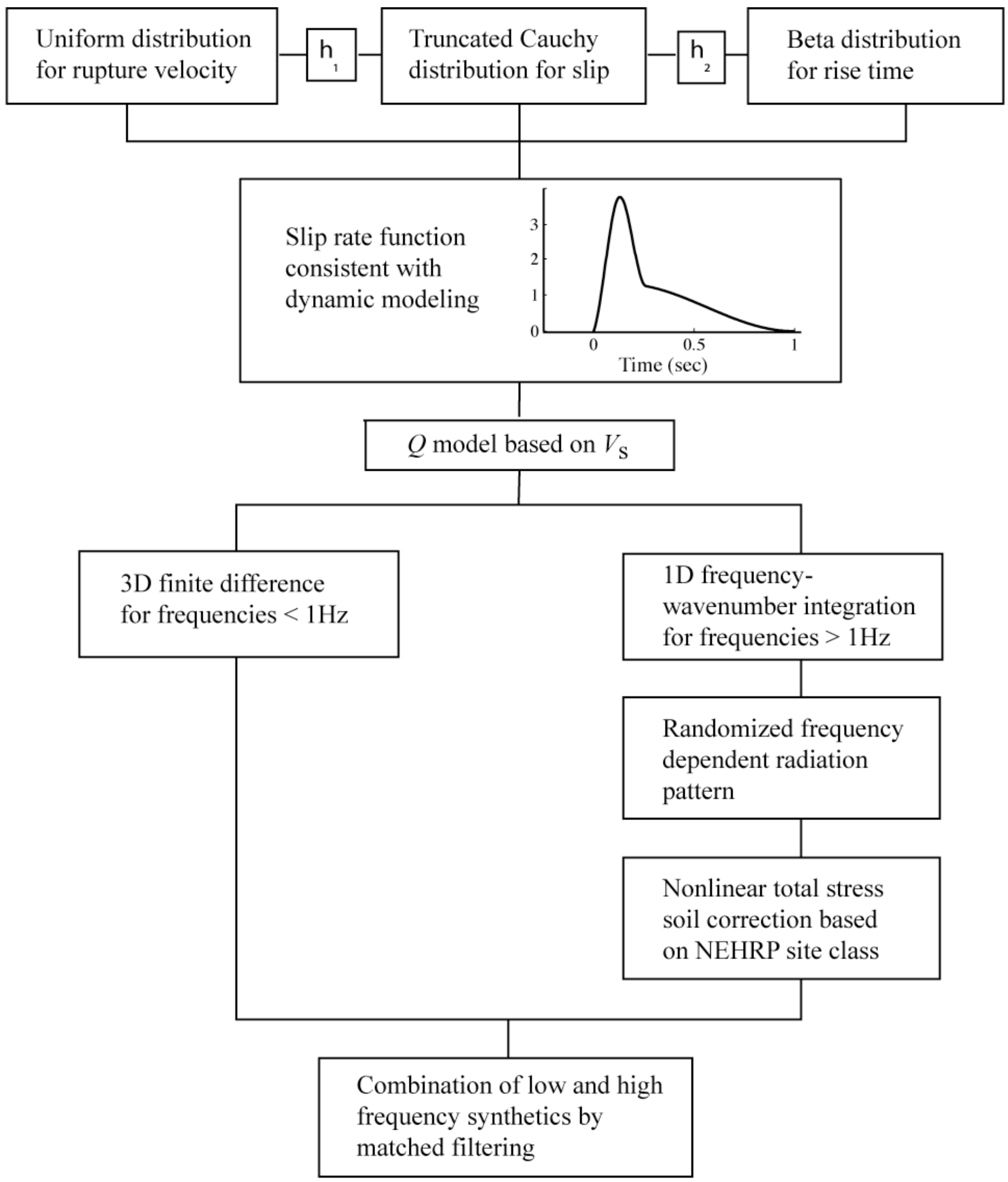

Figure 1: Flowchart of scheme for generating broadband synthetics (Liu et al., 2006).

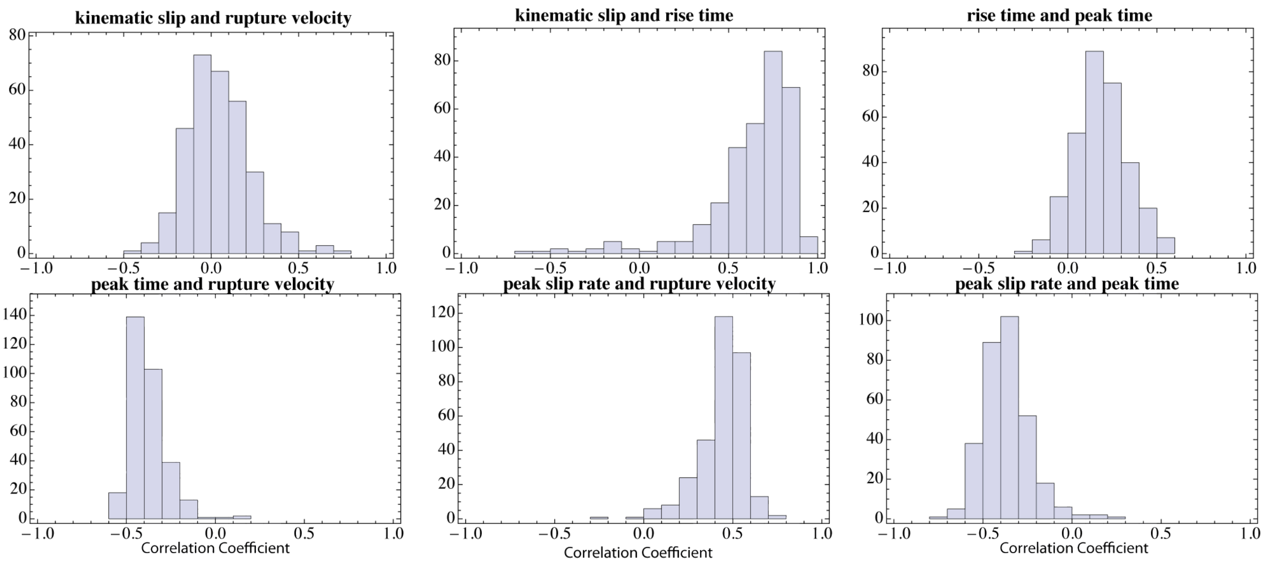

Figure 2: Histograms of computed spatial correlation coefficients for 315 ruptures and different parameter pairs. This result indicates that there is no correlation between slip and rupture velocity (Schmedes et al., 2010).