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A STOCHASTIC APPROACH TO PREDICTING SOURCE EFFECTS ON EXTREME GROUND MOTION

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We propose a stochastic approach for predicting extreme strong ground motion at low hazard levels. Our approach builds on previous work to characterize the scaling (*Mai and Beroza*, 2000) and spatial variability (*Mai and Beroza*, 2002) of earthquake slip. These stochastic slip distributions are used to develop the temporal behavior of slip using physically consistent stochastic-dynamic earthquake source models (*Guatteri et al.*, 2003) or pseudo-dynamic approximations to such models (*Guatteri et al.*, 2004). The premise of our approach is that we may be able to gain useful bounds on extreme ground motion by systematically exploring source models that are consistent with past earthquakes, but that occur at low probability and exhibit especially pernicious source properties, such as locally very high stress drop.

Source Parameter Scaling for Heterogeneous Slip Distributions

A number of scaling-relations have been proposed to estimate source dimensions for given magnitude **M** (*Wells and Coppersmith*, 1994 (henceforth denoted WC) , *Hanks and Bakun*, 2002; *Mai and Beroza*, 2000; *Somerville et al.*, 1999), however only the latter two studies considered the effect of heterogeneous slip. The MB-relations and the WC-relations seem similar, but differ substantially if we focus on the lower tails of the fault-length, *L*, and fault-width, *W*, populations. This translates into very different average displacement, *D*, and hence a very different level of strong ground motion.

For the repository site, the closest fault capable of generating moderate to large earthquakes is the Solitario Canyon Fault, located approximately 1.5 km to the west. From geological maps, we estimate the total length of the fault to be ~12 km, potentially separated into 3 individual segments (North segment ~5.4 km; Central segment ~2.6 km, and Southern segment ~4.0 km).

We consider a **M** = 6.75 earthquake on this fault to assess the source characteristics for extreme ground-motion simulations. Using the above lower-tail estimate of fault width, we calculate the expected average slip for two different fault lengths: $L_{surf} = 12\ km$, the length of the visible surface-fault expression, and $L_{subs} = 16\ km$, the assumed sub-surface fault length based on *Wells and Coppersmith*, 1994). For **M** = 6.75, we obtain $D = 3.0 – 4.0\ m$ and $D = 3.5 – 4.7\ m$ for the WC- and MB-relations, respectively. These are very high values, leading to very high stress drops (Figure 1) and potentially very damaging near-source ground motions. A recent earthquake with somewhat similar source characteristics, however, is the **M** = 6.6 Bam earthquake in 2003 that occurred on a very short fault (L ~15 km) with slip of 2-3 m locally (*Jonsson et al.,* 2004), resulting in devastating ground motions and the destruction of the city of Bam.

Representing and Simulating Slip Variability with Random Field Models

The variability of slip, slip-velocity, and rupture time maps directly into high frequency strong ground motions. It is therefore crucial to adequately model these source quantities in a self-consistent, physically constrained way. Our approach involves the characterization of spatially variable slip as a spatial random-field model (*Mai and Beroza*, 2002) that captures slip variability as observed in past earthquakes. In the second step, we model rupture time and rise time (peak slip-velocity) using principles of earthquake rupture dynamics.

The spatial random field can characterized in the spectral domain by its power spectral density, $P(k)$, where k is the wavenumber. *Mai and Beroza* (2002) found that a *von Karman* auto-correlation function slip with magnitude-dependent correlation length best represents the observed power spectral decay of earthquake slip models. Analyzing the spectral behavior of 44 source models, *Mai and Beroza* (2002) found that the spectral decay at high wavenumbers occurs with Hurst exponent $H = [0.8 - 1.0]$, while the correlation lengths scale with magnitude roughly as $a_x \approx 2.0 + \frac{1}{3} L$ (or $\log(a_x) \approx -2.5 + \frac{1}{2} M_w$), and $a_z \approx 1.0 + \frac{1}{3} W$ (or $\log(a_z) \approx -1.5 + \frac{1}{3} M_w$). Using such scaling relations ensures that our models will be statistically consistent with past earthquakes.

We use the static stress drop, $\Delta\tau$, associated with slip on the rupture plane, to develop the temporal slip evolution. We relate slip to stress using a convolutional integral (*Andrews, 1980*) expressed as a multiplication in the wavenumber domain, as $\Delta\tau(\mathbf{k}) = - K(\mathbf{k}) \cdot D(\mathbf{k})$ where $\tau(\mathbf{k})$ and $D(\mathbf{k})$ denote the two-dimensional stress drop $\Delta\tau(x,z)$ and slip-function $D(x,z)$, respectively in the wavenumber domain, and $K(\mathbf{k})$ is the static stiffness function. Recent work has calibrated this method against analytical solutions (*Okada, 1992*) and the method by *Bouchon, 1997*), extending the Andrews-model to include both in-plane and anti-plane stresses (*Ripperger and Mai, 2004*).

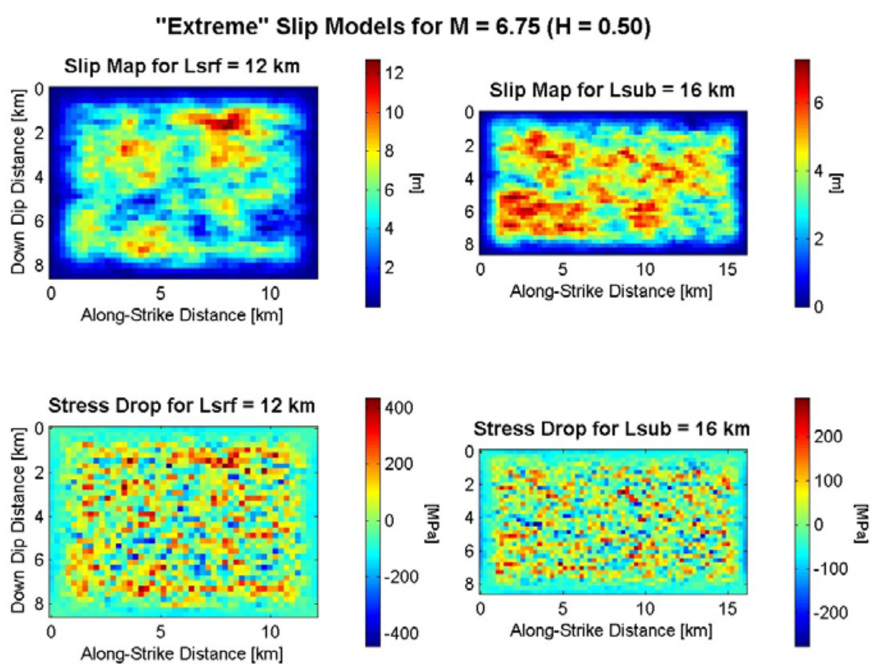

Figure 1. Slip (upper) and associate stress drop (lower) distributions for an Mw 6.75 earthquake on the Solitario Canyon fault under two assumptions of the extent of faulting (see text). Slip in the first model exceeds 10 meters and stress drops in both models are locally as high as several kilobars.

Physically Consistent Rupture Velocity and Rise Time

With the above approach, we generate physically consistent slip distributions, but rather than assuming a purely kinematic rupture time distribution, we develop physically consistent rupture propagation and the slip durations. We follow *Guatteri et al.* (2004) to compute the temporal slip evolution using the pseudo-dynamic source modeling approach. From stochastic-dynamic modeling of dynamic rupture *Guatteri et al.*, 2003) derived empirical relations linking fracture energy G_c to the stress-intensity factor $\Delta\tau \cdot L_c^{1/2}$, where L_c denotes the crack length (taken as the distance to the hypocenter). Fracture energy and stress drop control rupture velocity as low fracture energy promotes fast rupture propagation, while high fracture energy decelerates rupture propagation. This behavior is given by a relationship between rupture velocity, crack length, and stress drop for an anti-plane crack (*Andrews, 1976)*: $1 - v^2/\beta^2 = \pi^2 \cdot (R_c/2)^2$, where R_c is a dimensionless parameter: $R_c = \mu \cdot G_c / (\Delta\tau^2 \cdot L_c)$, v is the rupture velocity, β is the shear wave velocity, μ is the shear modulus, $\Delta\tau$ is the stress drop, and L_c is crack length.

The slip duration at each point on the fault is controlled by healing phases coming from the fault edges as well as healing phases generated internally on the rupture plane due to the prevailing stress conditions. *Guatteri et al.*, 2003) derived an empirical relationship that reflects such behavior of the rise time, using the previously computed rupture-onset time at each point and the total effective fault rupture duration.

The pseudo-dynamic source-modeling methodology is essentially kinematic, but it embodies a codification of relations between source parameters such as the joint variation of stress drop and rupture velocity in dynamic rupture models. The pseudo-dynamic approach allows us to efficiently generate a huge number of source models covering a wide parameter range, that are stochastically consistent with past earthquakes and have physically consistent rupture-velocity and rise-time distributions. It also allows us to explore strong-ground motions excited by extreme source models for which: (1) the source dimensions are chosen to be at the lower tails of fault-length/fault-width distributions; (2) average stress-drops as well as localized stress drops are on the order of kilobars; (3) rupture propagation velocity approach the local shear-wave velocity (or even become super-shear); (4) local slip-durations are very short, which in conjunction with large-slip will result in extreme peak-slip velocities.

Conclusions and Recommendations

(1) As currently formulated, our approach is based only on a small population of events that are predominantly either strike-slip or reverse faulting earthquakes. Moreover, while it reproduces the observed distribution of source parameters in past earthquakes, the constraints on slip are primarily statistical, rather than physical in nature.

(2) On the plus side, it may be that statistical bounds on the behavior of the source translate into tighter bounds on the source than are obtained through the application of the sort of "improbabilistic seismic hazard analysis" (the application of PSHA at extremely low probabilities of exceedence) that has been performed to date.

(3) Moreover, the pseudo-dynamic approach may be the ideal way to translate physical bounds on source parameters and the correlations among them, into physical bounds on ground motion.

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