Merging Dynamic Rupture Modeling and Strong-Motion Prediction

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Summary

Accurate prediction of the intensity and variability of strong ground motions for future large earthquakes depends on our ability to simulate realistic earthquake source models. Here we present a recently developed procedure to generate physically consistent earthquake rupture models and combine it with constraints on the rupture nucleation based on the analysis of the hypocenter positions of finite-source models. Although these so-called pseudo-dynamic source models are inherently kinematic, they are designed to emulate important characteristics of dynamic rupture. We construct pseudo-dynamic models by first generating a slip distribution as a realization of a spatial random field that is consistent in its scaling and spatial variability with slip distributions observed in past earthquakes. We then compute the static stress drop associated with the slip distribution which in turn is used to estimate the temporal evolution of slip through a set of empirical relationships derived from the analysis of spontaneous rupture models. Constraints on the hypocenter location, based on published finite-source models, are in agreement with simplified energy-budget considerations of dynamic rupture. While the relationships between the source parameters described in this paper are simplifications of the true complexity of the rupture physics, they help identify important interactions between source properties that are relevant for strong ground motion prediction, and should provide an improvement over purely kinematic models.

1. Introduction

Accurate strong-ground motion prediction for future large earthquakes hinges on several key factors. Wave propagation from the earthquake source to the site of interest depends on the complexity of Earth structure, both deterministically as expressed in three-dimensional basin effects, and stochastically as modeled in scattering theory. Site effects in the shallow, near-surface structure underneath the observation site may lead to either increased or decreased motions (compared to bed-rock level), and therefore further complicate strong-motion prediction. Complexity in the earthquake source adds yet another level of intricacy to ground-motion prediction methods. These key factors need to be addressed by scientists coming from different disciplines and cooperating very closely in order to improve our ability to accurately predict not only the intensity, but also the variability of near-source ground motions.

The results presented in this paper are concerned with the last of the aforementioned points, namely characterizing the earthquake source. Here we distill work over the past years in which we developed a so-called pseudo-dynamic source model (Guatteri et al., 2003, 2004) that is based on a suite of dynamic rupture models whose target slip distributions are consistent with slip complexity found in past earthquakes (Mai and Beroza, 2002). The temporal evolution of the rupture is constrained using empirical relationships derived from a large number of spontaneous dynamic rupture models, where we compute the static stress-drop based on a technique (Ripperger and Mai, 2004) that has been modified from the original approach by Andrews (1980).

While the point of rupture nucleation exerts a large influence on the dynamics of earthquake rupture and ground-motion generation, no model exists so far to constrain the hypocenter location in scenario earthquakes. We overcome this limitation by analyzing the hypocenter location using a database of more than 80 finite-source rupture models (Mai et al., 2004), leading to empirical rules for placing the point of rupture nucleation within a given/simulated slip (or stress-drop) distribution. These findings are also in
agreement with energy-budget considerations of dynamic rupture (Guatteri and Mai, 2003).

In the following we will highlight the key findings of the various studies mentioned in the previous sections.

2.1 Slip complexity in past earthquakes

Mai and Beroza (2002) used a spatial random field model to characterize the complexity of earthquake slip. A spatial random field is described either in space by its autocorrelation function, $C(r)$, or in the spectral domain by its power spectral density, $P(k)$, where $k$ is the wavenumber. Analyzing a set of 44 finite-source rupture models, Mai and Beroza (2002) found that a von Karman auto-correlation function, with correlation lengths $a_x, a_z$ that increase with magnitude, best represents the observed power spectral decay of earthquake slip models. The Hurst number $H$ is found to be independent of magnitude, $H = [0.8 – 1.0]$. The scaling of the correlation lengths, displayed in Fig.1, is given by the following expressions:

$$a_x \approx 2.0 + 0.33 L_{eff} \log(a_x) \approx -2.5 + 0.50 M_w$$ (1a)

$$a_z \approx 1.0 + 0.33 W_{eff} \log(a_z) \approx -1.5 + 0.33 M_w$$ (1b)

where $L_{eff}, W_{eff}$ denote the effective source dimensions.

In the course of this work we have generated heterogeneous slip distributions for scenario earthquakes with magnitudes $6.4 < M < 7.2$ whose source dimensions are computed following Mai and Beroza (2000). Having calculated the power-spectral density $P(k)$, the two-dimensional slip function is obtained by assuming random phase with the two-dimensional Fourier transformation carried out under the requirement of Hermitian symmetry to ensure a purely real valued slip function.

2.2 Calculating Static Stress-Drop from Final Slip

Several methods exist to compute the static stress changes on the fault plane of an earthquake given the distribution of final static displacements, but in particular for ground-motion prediction for many scenario earthquakes, the “classical” methods (Okada, 1992; Bouchon, 1997) are not advisable due to computational limitations. Recently, Ripperger and Mai (2004) have extended the approach by Andrews (1980) to incorporate both the slip-parallel and slip-perpendicular stress components and to compensate for depth-dependent rigidity. Comparing calculations for slip maps of past earthquakes using the modified Andrews method and the Okada solutions, we find that the stress-change results are accurate to about 1-2% of the maximum absolute stress change, while the computation time is greatly reduced. The method therefore provides a reliable and fast alternative to other methods. In particular, its speed will make computation of large suites of models feasible, thus facilitating the construction of physically consistent source characterizations for strong motion simulations.

2.3 Pseudo-Dynamic Source Model

The pseudo-dynamic source model allows constraining the temporal evolution of rupture consistent with rupture dynamics, in contrast to previous approaches in which local variations in rupture velocity or rise time were based on stochastic modeling (e.g., Hisada, 2000, 2001). Our pseudo-dynamic approach is built on several relationships between rupture velocity, crack length, fracture energy and stress drop. For a homogeneous anti-plane crack Andrews (1976) derived

$$1-v^2/\beta^2=\pi(R_c/2)^2$$ (2)

where the dimensionless parameter $R_c$ is given by

$$R_c=\mu G_c(\Delta\sigma/L_c).$$ (3)

$G_c$ denotes fracture energy, $v$ is rupture velocity, $\beta$ is the shear-wave velocity, $\mu$ is rigidity, $\Delta\sigma$ is stress drop, and $L_c$ denotes the crack length. Guatteri et al (2003) showed that Eq.2 also approximately holds for 3D-dynamic rupture with realistic stress heterogeneity.

Based on spontaneous dynamic rupture modeling, Guatteri et al (2003) developed an empirical linear relationship between fracture energy, crack length and stress drop, representing the growth of the stress-intensity factor with distance from the hypocenter (Fig 2):

![Circular Average (a)](image-url)
where $W$ denotes the fault width and $V_{\text{max ref}}$ represents a reference peak-slip velocity. The pulse-width $T_p$ and the slip-rise time, $\tau_r$, are then computed in a two-step process such that their distributions are consistent with the results found in our spontaneous dynamic rupture models. Figure 4 displays the application of the pseudo-dynamic approach to the 1984 Morgan Hill, California, earthquake, using the slip distribution by Beroza and Spudich (1988).

2.4 Constraints on Hypocenter Location

While the spatial complexity of earthquake slip has been studied both theoretically and by analyzing the inferred slip distributions of past earthquakes, the hypocentral position with respect to the final slip has received little attention. However, the position of the hypocenter, both with respect to the overall fault dimensions and the small-scale variability in slip (or stress) on the fault, greatly affects ground motion generation.

Mai et al. (2004) use a database of more than 80 finite-source rupture models for more than 50 earthquakes (Mw = 4.1-8.1) with different faulting styles occurring in both crustal and subduction environments to analyze the location of the hypocenter within the fault and to consider the correlation between hypocenter location and regions of large slip. They find that rupture in strike-slip and crustal dip-slip earthquakes tend to nucleate in the deeper sections of the fault, while subduction earthquakes do not show this tendency.
More importantly, ratios of the hypocentral slip to either the average or the maximum slip show that rupture can nucleate at locations with any level of relative displacement. Rupture nucleates in regions of very large slip \((D \geq 2/3 \, D_{\text{max}})\) in only 16% of the events, in regions of large slip \((1/3 \, D_{\text{max}} < D < 2/3 \, D_{\text{max}})\) in 35% of the events, and in regions of low slip \((D \leq 1/3 \, D_{\text{max}})\) in 48% of the events. Ruptures that nucleate in regions of low slip, however, tend to nucleate close to regions of large slip, and encounter a zone of very large slip within half the total rupture length (Fig 5). These findings are consistent with simplified energy-budget considerations for dynamic rupture models.

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References


