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**Spectral Elastodynamic Simulations of Complex Rupture Phenomena and Slip Histories on Planar Faults**

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(studies with Nadia Lapusta, Alain Cochard, Bruce Shaw, and Koji Uenishi)

The studies are in continuation of research to understand how elastodynamic wave effects and, sometimes, strong heterogeneities can interact with laboratory-justified (or speculated) constitutive response to predict earthquake behavior. They involve planar faults, with use of the accurate and efficient spectral elastodynamic procedures that we have developed, sometimes including the treatment of rupture phenomena on faults with realistic depth-variation of frictional response properties because of variation with depth of overburden and, especially, temperature.

The first three topics give abstracts of papers published in late 2000, each representing the completion of a multi-year study funded or in part by SCEC. These are:

***Elastodynamic analysis for slow tectonic loading with spontaneous rupture episodes on faults with rate- and state-dependent friction*** (N. Lapusta, J. R. Rice, Y. Ben-Zion and G. Zheng, Journal of Geophysical Research, vol. 105, pp. 23,765-23,789, 2000): We present an efficient and rigorous numerical procedure for calculating the elastodynamic response of faults subjected to slow tectonic loading processes of long duration within which there are episodes of rapid earthquake failure. This is done for a general class of rate- and state-dependent friction laws with positive direct velocity effect. The algorithm allows us to treat accurately, within a single computational procedure, loading intervals of thousands of years and to describe, for each earthquake episode, initially aseismic accelerating slip prior to dynamic rupture, the rupture propagation itself, rapid postseismic deformation which follows, and also ongoing creep slippage throughout the loading period in velocity strengthening fault regions. The algorithm first separates the elastodynamic stress transfer functional into its long-time static limit and a wave-mediated dynamic part. The latter localizes the effects of the prior deformation history in convolution integrals on slip velocity with rapidly decaying kernels. Truncation of these convolutions allows to simulate long processes without the necessity to deal with all prior deformation history at each time step. Throughout the calculation, time steps can vary by several orders of magnitude. We present principles underlying their choice, as dictated by the current values of slip velocities, parameters of the constitutive law and stability considerations. This variable time stepping makes the number of time steps during slow deformation periods numerically manageable while still capturing the details of both the nucleation and dynamic propagation phases. Proper space and time discretization, and a new second-order accurate updating scheme that we develop, ensure the reliability of the results which can be verified through grid and time-step refinement. The methodology is presented using the 2-D anti-plane spectral formulation, and illustrated for a 2-D crustal strike-slip fault model with depth-variable properties. The procedures can be readily extended to the 2-D in-plane and 3-D spectral formulations and, with certain modifications, to the space-time boundary integral formulations as well as to their discretized development using finite-difference or finite-element methods.

***Existence of continuum complexity in the elastodynamics of repeated fault ruptures*** (B. E. Shaw and J. R. Rice, Journal of Geophysical Research, vol. 105, pp. 23,791-23,810, 2000): What are the origins of earthquake complexity? The possibility that some aspects of the complexity displayed by earthquakes might be explained by stress heterogeneities developed through the self-organization of repeated ruptures has been suggested by some simple self-organizing models. The question of whether or not even these simple self-organizing models require at least some degree

of material heterogeneity to maintain complex sequences of events has been the subject of some controversy. In one class of elastodynamic models, previous work has described complexity as arising on a model fault with completely uniform material properties. Questions were raised, however, regarding the role of discreteness, the relevance of the nucleation mechanism, and special parameter choices, in generating the complexity that has been reported. In this paper, we examine the question of whether or not continuum complexity is achieved under the stringent conditions of continuous loading, and whether the results are similar to previously claimed findings of continuum complexity or its absence. The elastodynamic model that we use consists of a 1-D fault boundary with friction, a steady slowly moving 1-D boundary parallel to the fault, and a 2-D scalar elastic media connecting the two boundaries. The constitutive law used involves a pair of sequential weakening processes, one occurring over a small slip (or velocity) and accomplishing a small fraction of the total strength drop, and the other at larger slip (or velocity) and providing the remaining strength drop. The large-scale process is motivated by a heat weakening instability. Our main results are as follows. (1) We generally find complexity of type I, a broad distribution of large event sizes with nonperiodic recurrence, when the modeled region is very long, along strike, compared to the layer thickness. (2) We find that complexity of type II, with numerous small events showing a power law distribution, is not a generic result but does definitely exist in a restricted range of parameter space. For that, in the slip weakening version of our model, the strength drop and nucleation size in the small slip process must be much smaller than in the large slip process, and the nucleation length associated with the latter must be comparable to layer thickness. This suggests a basis for reconciling different previously reported results. (3) Bulk dispersion appears to be relatively unimportant to the results. In particular, motions on the fault plane are seen to be relatively insensitive to a wide range of changes in the dispersion in the bulk away from the fault, both at long wavelengths and at short wavelengths. In contrast, the fault properties are seen to be very important to the results. (4) Nucleation from slip weakening and time-dependent weakening showed similar large-scale behavior. However, not all constitutive laws are insensitive to all nucleation approximations; those making a model "inherently discrete" and hence grid-dependent, in particular, can affect large scales. (5) While inherent discreteness has been seen to be a source of power law small-event complexity in some fault models, it does not appear to be the cause of the complexity in the attractors examined here, and reported in earlier work, fortuitously in the special parameter range, with the same class of continuum fault models and same or very similar constitutive relations. Continuum homogeneous dynamic complexity does indeed exist, although that includes type II small-event complexity only under restricted circumstances.

***Fault rupture between dissimilar materials: Ill-posedness, regularization and slip-pulse response*** (A. Cochard and J. R. Rice, Journal of Geophysical Research, vol. 105, pp. 25,891-25,907, 2000): Faults often separate materials with different elastic properties. Nonuniform slip on such faults induces a change in normal stress. That suggests the possibility of self-sustained slip pulses (Weertman, JGR., 1980) propagating at the generalized Rayleigh (GR) wave speed even with a Coulomb constitutive law (i.e., with a constant coefficient of friction) and a remote driving shear stress that is arbitrarily less than the corresponding frictional strength. Following Andrews and Be-Zion (BSSA, 1997) (ABZ), we study numerically, with a two-dimensional (2-D) plane strain geometry, the propagation of ruptures along such a dissimilar material interface. However, this problem has been shown to be ill-posed for a wide range of elastic material contrasts. Ranjith and Rice (JMPS, 2001) (RR) showed that when the GR speed exists, as is the case for the material contrast studied by ABZ, the problem is ill-posed for all values of the coefficient of friction,  $f$ , whereas when it does not exist, the problem is ill-posed only for  $f$  greater than a critical value. We illustrate the ill-posedness by showing that in the unstable range the numerical solutions do not converge through grid size reduction. By contrast, convergence is achieved in the stable range but, not unexpectedly, only dying pulses are then observed. RR showed that among other regularization procedures, use of an experimentally based law, in which the shear strength in response to an abrupt change in normal stress evolves continuously with time or slip toward the corresponding Coulomb strength, provides a regularization. (Classical slip-weakening or rate- and state-dependent constitutive laws having the same kind of abrupt response as Coulomb friction also do not

regularize the problem.) Convergence through grid size reduction is then achieved in the otherwise ill-posed range. For sufficiently rapid shear strength evolution, self-sustained pulses are observed. When the GR wave speed exists, they propagate essentially at that velocity and, in consistence with Weertman's analysis, the propagation occurs only in one direction, which is that of slip in the more compliant medium. When the GR wave speed does not exist, similar self-sustained pulses propagate at about the slower S wave speed and in the same direction. RR also suggested that for sufficiently high coefficient of friction, another kind of (less unstable) self-sustained pulses, propagating at a velocity close to the slower P wave speed and in the opposite direction, could also exist. We numerically verify that prediction.

***Earthquake nucleation and early propagation as affected by prior events:*** We have studied earthquake nucleation and early propagation during sequences of model earthquakes in a 2-D model of a vertical strike-slip fault with standard depth-variable rate and state friction. The methodology (Lapusta et al., *JGR*, 2000) incorporates both truly slow, tectonic loading and all dynamic features. It allows us to treat accurately, within a single computational procedure, loading intervals of thousands of years and to calculate, for each earthquake episode, initially aseismic accelerating slip (nucleation process), the resulting dynamic rupture break-out and propagation, post seismic deformation, and ongoing slippage throughout the loading period in creeping fault regions.

Rate and state friction incorporates a characteristic slip distance  $L$  for evolution of frictional strength. For fixed other parameters, the nucleation size (size of the quasi-statically slipping patch that precedes the dynamic rupture break-out) is proportional to  $L$ . We study how earthquake sequences change as we decrease  $L$ , approaching the laboratory range of tens of microns (too small to be computationally feasible). As  $L$  decreases, small events appear near the brittle-ductile transition at the bottom of the seismogenic (velocity-weakening) zone. For the particular depth-variable fault model studied by Lapusta et al. (*ibid*), a simulation with  $L = 8$  mm produces a periodic sequence of large events (sequence I), while a simulation with  $L = 2$  mm results in the sequence of a large and a small event (sequence II), as do the simulations with  $L = 1$  mm and 0.5 mm. In the case with  $L = 0.14$  mm (done so far only quasi-dynamically; we intend to redo it with full dynamics), the sequence is more elaborate, with large events interspersed by three smaller events.

The nucleation of the large and small events is very similar, as manifested by plots of slip, slip velocity, moment rate, and moment acceleration. This means that observing the nucleation and beginning of a model earthquake, it is impossible to tell whether the final size of the event will be large or small. The final size of the event is determined by the conditions on the fault region that the event is propagating into, rather than by the nucleation process.

We observe that moment acceleration during initial stages of dynamic rupture propagation can have "bumps" and subsequent "speed-ups". This is consistent with observations, e.g. as reported by Ellsworth and Beroza (*Science*, 1995), who attribute these features to either processes in the preslip region or a special cascade structure of the fault. Our simulations show that such irregular moment acceleration (to which velocity seismograms are proportional) can be caused by heterogeneous stress distribution left by previous events. For the large event of the sequence II, moment acceleration grows initially, then decreases almost to zero during rupture propagation over the region that slipped in the previous small event, and then again abruptly grows, even faster than initially, when the rupture reaches the region of stress concentration left by the arrest of the previous event. Such a "bump" and "speed-up" is not observed for an event of the sequence I which does not have small events.

***Critical aseismic slip zone size at nucleation:*** We have addressed the following problem of nucleation in the context of a linearly slip-weakening model in 2D. A fault sustains a nonuniform stress distribution which is locally peaked at some location. Tectonic loading causes that stress to increase at a spatially uniform rate everywhere on the fault. Ultimately that peak stress reaches the strength level to initiate slip weakening, and a zone of aseismic slip initiates from that peak-stressed

point and slowly enlarges. Treating this as a quasistatic problem, we show that the slip rate increases without bound, i.e., that there ensues a dynamically controlled instability, when the slipping zone has grown to a critical size. We prove that the slipping zone size at instability is a system constant for a given material and slip-weakening rate. That is, the size is independent of the nature of the loading stress distribution, i.e., of whether its peak is broad or narrow or is of one mathematical form or another.

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