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PHYSICS-BASED SIMULATION OF EARTHQUAKE OCCURRENCE IN FAULT SYSTEMS

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Introduction

This is a new project that began in 2005. The project goals are to develop and apply a large-scale 3D physics-based earthquake simulator for a) investigation of earthquake processes in geometrically complex fault systems, and b) use with the SCEC community fault model for evaluations of earthquake probabilities.

To address these goals the simulator will be

1) sufficiently flexible to incorporate alternative models of earthquake source processes and input parameters;
2) capable of modeling earthquake occurrence over a large range of length and time scales to permit comparisons with earthquake catalogs and paleoseismology data;
3) fully three-dimensional to properly represent fault interactions and to permit comparisons with deformation observations;
4) able to model time-dependent fault interactions, as well as foreshocks and aftershocks, by incorporating time-dependent earthquake nucleation inherent to rate- and state-dependent friction; and
5) suitable for implementation with complex fault system geometry, including the SCEC community fault model at a resolution appropriate to items 1) through 4).

The simulator will implement the SCEC community fault model at a 1km resolution, to permit comparisons with the southern California instrumental catalog data at a minimum earthquake magnitude threshold of about M3.5. Recent work [Dieterich, 2004, 2005] demonstrates that slip of geometrically complex faults entails a variety of effects that do no arise in models of planar faults. These include non-linear scaling, model-size dependence, and accumulating off-fault deformation. Consequently, particular attention is being given to scaling issues and to potential computational artifacts associated with slip interactions over a very wide range of length scales. In addition, this model specifically addresses stress accumulation and resulting seismicity that occurs off of the explicitly represented faults in the model.

Overview of Modeling Approach

To meet the goal of repeatedly simulating long earthquake catalogs over a wide range of length scales requires a high degree of computational efficiency. Clearly, repeated simulations of synthetic catalogs of 10^5 or more earthquakes using a detailed fully dynamical deterministic calculation of every earthquake are not feasible with current computational technology. Appropriate large-scale approximations and simplifications must be developed to allow the computations to be done in a reasonable time.

A method developed and tested by Dieterich [1995] for single planar faults is being adapted and generalized for simulation of earthquakes on a 3D system of explicitly modeled faults. This quasi-dynamical approach approximates the gross dynamics of the earthquake source, and it incorporates fault aging and nucleation processes implicit to rate- and state-dependent friction. The simulations avoid solution of systems of simultaneous equations, and use event-driven computational steps, instead of time stepping at closely spaced intervals. Fault segments may be at one of three sliding states, which correspond to a fully locked condition with time dependent strengthening (state 0), an incipient slip condition with time- and stress-dependent nucleation prior to unstable slip (state 1), and seismic slip at speeds determined by dynamic shear impedance criteria and sliding resistance (state 2). Computational events, which update stressing conditions, occur at the transitions between states.

Slip of geometrically complex faults induces heterogeneous stresses in the medium in which the faults are embedded. In elastic models, these stresses grow without limit as slip increases and sequester strain energy that would otherwise be released in fault slip, and lead to non-linear scaling of slip with fault size [Dieterich, 2004]. Representing the inevitable yielding that occurs in response to this stress build-up is important because a) yielding will be expressed in part, or wholly, as "off fault" seismicity; and b) yielding determines the strength of barriers that control the non-linear scaling of slip on explicitly modeled faults. In the fault system simulator, off-fault yielding and seismicity will be represented using a rate- and state-dependent formulation gives the rate of seismic activity in response to a stressing history (Dieterich, 1994). Use of this formulation provides a means to simulate long-term seismicity and aftershocks in a manner that is fully consistent with the simulations of earthquakes on the explicitly modeled faults.

Accomplishments in 2005

Program design. A structure and design of the simulation code was developed in 2005. This included working out the details for generalizing the 3D interactions among fault segments with different orientations and modes of slip, and design of a flexible modular program structure to accommodate alternative characterizations of fault processes.

Interaction matrices. Interactions among the fault elements are represented by an array of 3D elastic dislocations. The computations employ stresses and slips at the center of square elastic dislocation elements. Shear stress in the prescribed direction of fault slip (τ) and normal stress (σ) at the center of each fault element are found by summing the slip contributions over all elements,

$$\tau_i = T_{ij} d_j \ , \ \ \sigma_i = N_{ij} d_j \ , \text{ and }, \ i, j = 1, 2, \ldots, n \qquad (1)$$

where, (1) employs the summation convention, n is the number of fault elements, d_j is the array of segment slips, and the coefficients T_{ij} and N_{ij} are obtained from the Okada (1992) solutions for rectangular elastic dislocations using the relevant distance, segment orientation, and slip vector information. In 2005 critical programming tasks were completed for generating the T_{ij} and N_{ij} matrices for interaction among segments with any orientation and fault slip vector (*e.g.* a strike-slip segment acting on a reverse fault segment with a different orientation).

Nucleation with variable normal and shear stress. A generalized form of the Dieterich [1992] solutions for nucleation has been found for Coulomb stressing. To represent state 1 conditions, the original planar-fault simulator employed analytic solutions for nucleation of unstable slip under conditions of constant normal stress. However, normal stress is not constant in the fault-system simulations. Between computational steps both shear and normal stresses vary to give a constant rate of Coulomb stressing. Under conditions where nucleation is in progress ($\theta >> D_c / \dot{\delta}$), it can be shown that the local acceleration of slip is fully described by

$$d\omega = \frac{-1}{A\sigma}\left[Cdt + \omega d\tau + (\mu - \alpha)\omega d\sigma\right] \quad , \tag{2}$$

where slip speed $\dot{\delta} = 1/\omega$, C is a constant term containing model and constitutive parameters, μ is the nominal coefficient of friction during state 1 slip, α is a material parameter ($0 \le \alpha \le \mu$) governing the effect of normal stress change on the evolution of θ, and A is the rate constant in the rate- and state-dependent friction formulation. Assuming the term ($A\sigma$) is constant (small σ change) (2) this reduces to

$$d\omega = \frac{-1}{A\sigma}\left[Cdt + \omega dS\right], \tag{3}$$

where S a modified Coulomb stress function

$$dS = \tau - \mu'\sigma \quad \text{with} \quad \mu' = \mu - \alpha \ .$$

Solutions of (3) are easily obtained for the evolution of slip speed and time to instability at constant $\dot{S}$. Discovery of this solution is an important step, because it means the computational scheme used for planar fault can be implemented directly without resorting to time-consuming numerical solutions of the nucleation process. This solution will also be of use for other applications.

Off-fault stress relaxation and seismicity. In elastic models with complex fault geometry, interactions among segments give rise to stresses that increase without limit as slip increases. Eventually in a real material, yielding must take place whereby something like steady-state condition exists in which the stressing is balanced by stress relaxation through the yielding process. As noted above, the modeling approach that will be implemented to represent these effects is based on a rate- and state-dependent formulation for earthquake rates. In 2005 formulation of the initial modeling approach was completed and a trial computer program was developed for testing purposes.

Figures 1, 2 and 3 illustrate some examples obtained with this modeling approach. For implementation with the simulator input stresses will be determined from Okada dislocation solutions using the computed fault slip. In these examples, the input stresses were obtained from an existing 2D model for slip on a fault with a random fractal roughness. Figure 1 gives results for the average long-term seismicity rate as a function of distance. The calculations assume a steady-state condition for yielding (in the form of seismicity) that balances the stressing from continuing fault slip at some constant rate. The average seismicity rate, as a function of distance from the fault, follows for these 2D models a power law scaling relationship

$$R \propto d^{-n} \ , \text{ where } \ n = 2 - H \tag{4}$$

where H is the Hurst exponent used to generate the random fractal fault topography. For calculations of faulting in 3D this result suggests $n = 3 - H$.

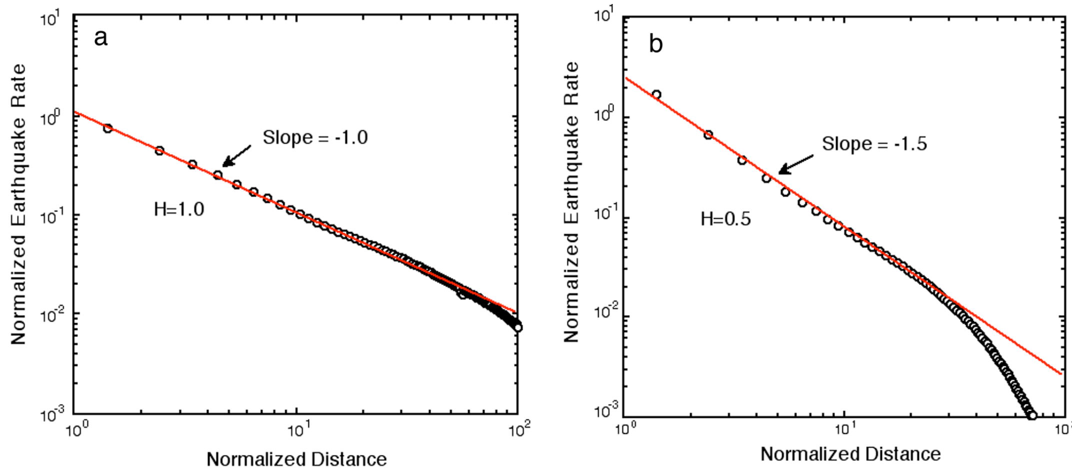

Figure 1. Earthquake rates induced by the heterogeneous stresses from slip of a single fault with a random fractal roughess. Earthquake rate is the average of long-term rate as a function of distance from a fault random fractal roughness. a) Fractal fault with a Hurst exponent of 1.0. b) Hurst exponent of 0.5. Vertical scale is arbitrary and depends on long-term fault slip rate, the magnitude-frequency distribution, and scaling of lengths.

Figures 2 and 3 illustrate the effects of the amplitude of fault roughness on calculations for aftershock rates (normalized by the local long-term average rate at each grid point) immediately after a slip event on a random fractal fault. Note that for a planar fault no aftershocks occur within the region adjacent to the region of fault slip (stress shadow effect). However, the stresses arising from slip of a fault with even small amplitude roughness are sufficient to induce considerable seismicity near the fault within the stress shadow region. With increasing amplitude of the fractal roughness, the aftershock intensity within the rupture zone is comparable to that at ends of the rupture segment (Figure 3).

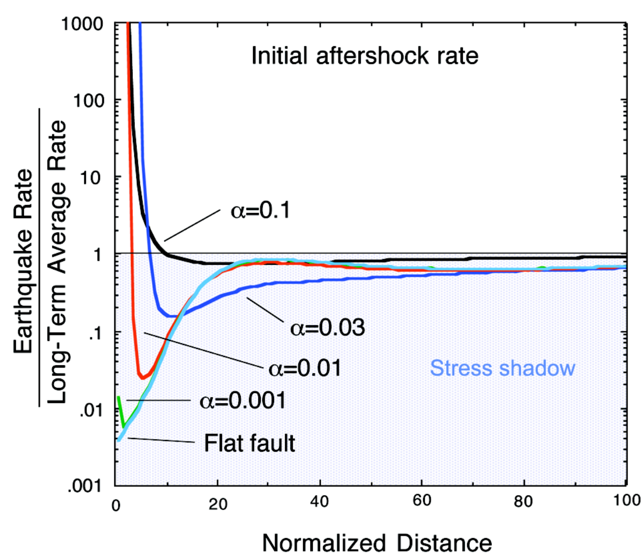

Figure 2 Average initial rate of aftershocks as a function of distance from fault, normalized by the long-term average background rate. Normalized earthquake rupture length=510. Note that as roughness (α) increases, the aftershock stress-shadow obtained for slip on a planar fault is overwhelmed by the effect of heterogeneous stresses in the non-planar fault model.

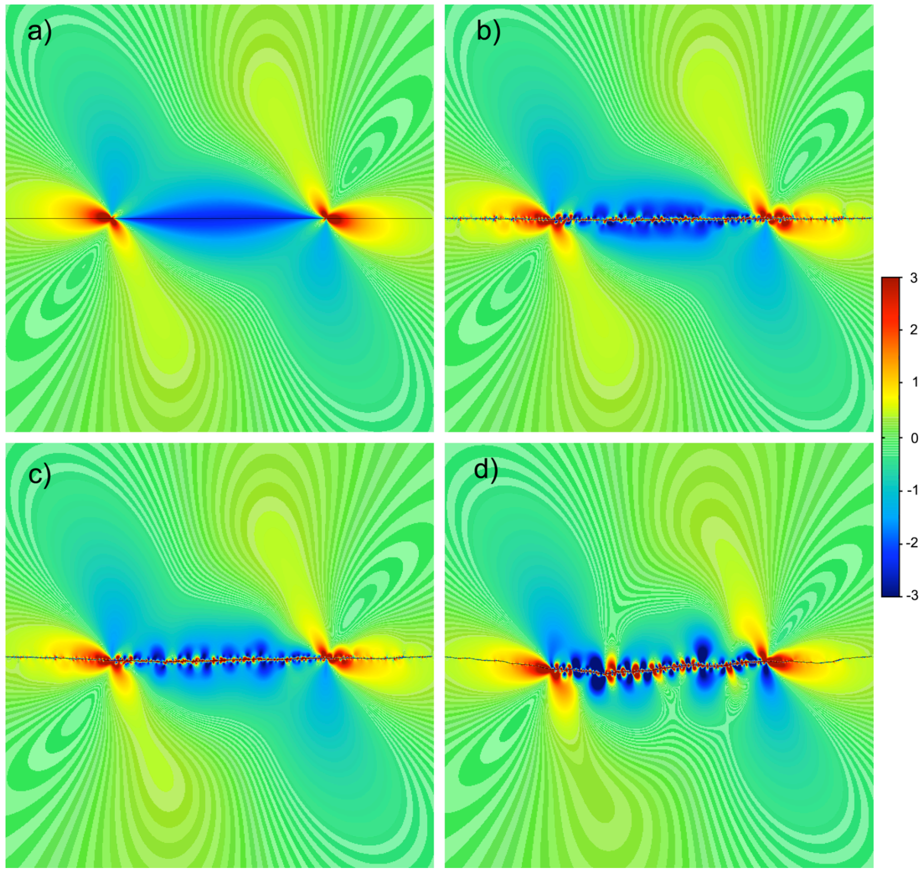

Figure 3. Spatial distributions of aftershock for different amplitudes of fault roughness. Logarithmic scale of initial aftershock rate normalized by the long-term average rate. a) Planar fault. b) Fractal fault with amplitude factor α=0.01. c) Fractal fault with amplitude factor α=0.03. b) Fractal fault with amplitude factor α=0.1.

Student Participation in Project

Kieth Torres an undergraduate major in computer science, and Sitara Wijeratne, an undergraduate in physics and mathematics, participated in this project as summer research assistants. Kieth Torres worked on the programming of the Okada dislocation solutions for determining the interaction matrices. Sitara Wijeratne helped to develop some utility programs that will be useful for importation of the SCEC community fault model and its conversion to an assembly of rectangular dislocation elements.

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