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The dependence of fault strength on rapid changes in normal stress and their implications for dynamic fault rupture

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PROPOSAL CATEGORY:
B: Integration and Theory

SCIENCE OBJECTIVES ADDRESSED:
A10, A9, A6

Statement of the Problem

Large-scale physics-based computational simulations of earthquake ruptures have been undertaken by SCEC to assess potential strong earthquake ground motions in southern California. The simulations generally do not include the spontaneous earthquake initiation process for complexities in both computation and modeling. Our studies of earthquake nucleation on complex 3D fault systems indicate that fault geometry and properties together with initial stress conditions strongly influence where and when earthquake nucleation occurs (Zhang, et al., 2004, 2006, Fang, et al., 2010, 2011, 2012). For a rupture simulation along a pre-defined fault, the point of rupture initiation strongly affects ground motions. For this reason, we proposed to investigate how earthquake earthquakes are nucleated in geometrically and frictionally complex fault systems. In particular, we intended to develop a comprehensive mechanical model that allows us to study earthquake nucleation on general non-planar faults and then implement 3D simulations of the San Andreas fault at the resolution used for the large-scale rupture simulations. We hoped the results can then be directly used as to set initial conditions for the large-scale rupture simulations.

Results

The project has been initially carried out by PhD student Zijun Fang in Mechanical Engineering who has incorporated the normal stress, rate and state dependent friction law (Linker and Dieterich, 1992) into a variational boundary integral method (Xu and Ortiz, 1993, Xu, 2000; Zhang, et al., 2004, 2006) that can be used to study the slip on fully three dimensional non-planar fault systems under general loading. Figure 1 shows an example problem we have studied using this model. Figure 1a) shows a horizontal cross section of a 3D strike slip fault with a ramp between two planar segments. Homogeneous frictional properties are assumed in these preliminary studies. The ramp, characterized by the bend angle, is under combined shear and normal stress when the external loading is parallel with strike. The elastic interaction due to slow preseismic slip alters the normal stress along the whole fault, resulting in heterogeneous normal stress. The variation of normal stress is controlled by the bend angle, i.e., the larger the angle, the more severe the variation. Figures 2 b) and 2 c) show the velocity fields on the whole fault at the time of earthquake nucleation. The only difference between the two fault systems b) and c) is that the bend angle is 2.9 degrees in b) and 8.6 degrees in c). The results show that as the bend angle increases, earthquake nucleation migrates from the middle of the ramp to the edges of the main segments. In addition, the size of the nucleation patch is also strongly affected by the bend angle. b

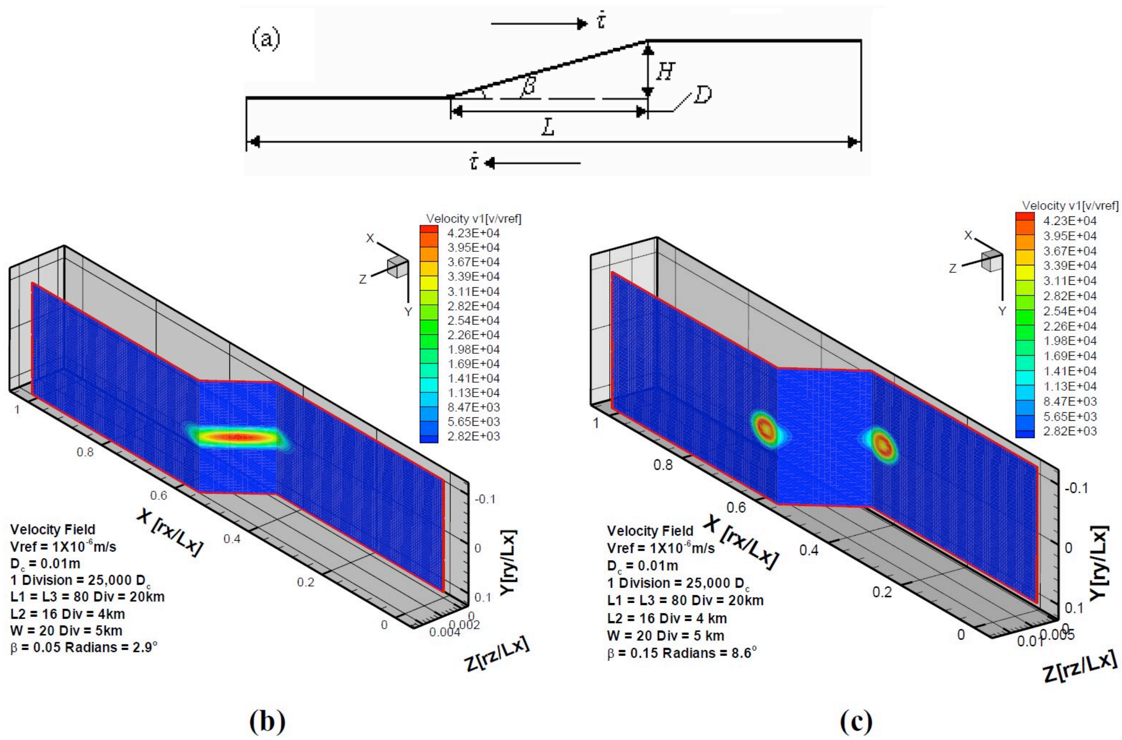

Fig 1. a) A schematic configuration of a strike slip fault with a ramp between two fault segments. (b) Earthquake nucleation velocity field when the bend angle b is 2.9 degrees. (c) Earthquake nucleation velocity field when the bend angle b is 8.6 degrees.

In order to carry out more realistic analysis for large scale three dimensional faults, we developed a new numerical approach that can efficiently construct the elastic fracture matrices of three dimensional faults in a half space using a combined dislocation continuity method and direct boundary method. The three displacement components of each element of the fault are modeled as three dislocation loops placed along the sides of the element. The stress field of each element in infinite space can be effectively calculated as the summation of the stress of dislocation segments along the sides of the element following Devincre's formulation of the stress fields of a dislocation segment in the three dimensional space (1995).

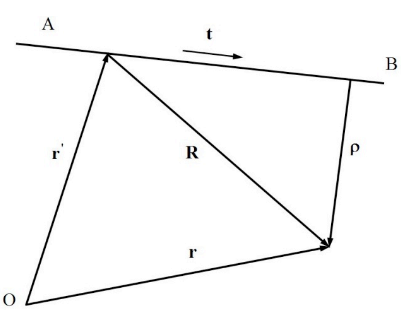

Fig. 2 Geometry of a displacement segment

Consider a straight dislocation segment lies between $\boldsymbol{r}_A$ and $\boldsymbol{r}_B$ as shown in the figure 2, its stress is given by

$$\sigma_{ij}^{A\rightarrow B} = \sigma_{ij}(\boldsymbol{x}_B) - \sigma_{ij}(\boldsymbol{x}_A)$$

where

$$\sigma_{ij}(x) = \frac{\mu}{\pi Y^2}\left\{[\boldsymbol{bYt}]_{ij} - \frac{1}{(1-\nu)}[\boldsymbol{btY}]_{ij} - \frac{(\boldsymbol{b},\boldsymbol{Y},\boldsymbol{t})}{2(1-\nu)}\left[\delta_{ij} + t_i t_j + \frac{2}{Y^2}\left(\rho_i Y_j + \rho_j Y_i + \frac{L}{|R|}Y_i Y_j\right)\right]\right\}$$

$$[\boldsymbol{abc}]_{ij} = \frac{1}{2}\left[(\boldsymbol{a}\times\boldsymbol{b})_i c_j + (\boldsymbol{a}\times\boldsymbol{b})_j c_i\right]$$

$$\boldsymbol{R} = \boldsymbol{r} - r',\ L = \boldsymbol{R}\cdot\boldsymbol{t},\ \boldsymbol{\rho} = \boldsymbol{R} - L\boldsymbol{t},\ \boldsymbol{Y} = \boldsymbol{R} + |\boldsymbol{R}|\boldsymbol{t} = (L + |\boldsymbol{R}|)\boldsymbol{t} + \boldsymbol{\rho}.$$

To construct the fracture matrix of a fault system in the half space, we view the Earth surface as the surface of a very large crack surface and treat the fault system and the crack of the Earth surface embedded in the infinite elastic media. Using the displacement discontinuity method, we can construct a system matrix

$$\begin{Bmatrix} K_{cc} & K_{cs} \\ K_{sc} & K_{ss} \end{Bmatrix}\begin{Bmatrix} \Delta u_c \\ u_s \end{Bmatrix} = \begin{Bmatrix} t_c \\ 0 \end{Bmatrix}$$

where Δu_c and u_s represents the displacement discontinuities (or slip) on the fault and displacements on the Earth surface. t_c are the traction components on the fault. Since only the evolution of the displacement and stress on the faults are involved in the simulation of nucleation of slip. We further reduce the above equation into

$$(K_{cc} - K_{cs}K_{ss}^{-1}K_{sc})\Delta u_c = D_{cc}\Delta u_c = t_c$$

Here the relative smaller matrix D_{cc} which relates the slip and stress on the fault is explicitly constructed and can be used repetitively to calculate the evolution of the slip process.

We note several advantages of the above formulation compared to other formulations using fundamental dislocation solutions in the half space. First the program and calculation are much more systematic and expedient because the tensor formulation of the stress of a general segment in three dimensional space. Second the method is also applicable for non-planar surface.

We have done the program and the method works effectively. Unfortunately, we have virtually stopped pursuing the implementation of the our new approach to realistic San Andreas fault because of the lack of funding to support the new graduate student to continue working on earthquake problems in mechanical engineering department.

Impact

The method developed in this project may be of great use in producing realistic earthquake nucleation locations for scenario earthquakes in Southern California and beyond. In turn, better estimates of nucleation locations may help reduce uncertainty in ground motion models via a better estimate of effects such as directivity. In addition to its scientific results, the project also helped train an engineering graduate student (Zijun Fang) in fault dynamics; this student went on to a seismology post-doc at Stanford, and now has a promising career in industry.

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