

Dynamic rupture front interaction on 3D planar fault

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Abstract

We demonstrate a rupture front focusing phenomenon at the initial stage of earthquake, which causes high slip rate pulses and therefore generates high frequency seismic waves. In this computation, we assume a pre-slip region, where stress has already lowered quasi-statically to the dynamic friction level. And due to the pre-slip, we suppose a stress concentration at the edge of pre-slip area. Then a dynamic rupture starts at a certain point on the rim of the pre-slip region. We could observe a rupture front focusing that causes high slip rate pulse. We also observed a high frequency pulse in ground velocity seismogram. We computed a double pre-slip model, where two pre-slip region exist, and found that multiple pre-slips enhances this effect.

Introduction

Recently, the initial phase of earthquake ruptures have been discussed based on the observation of very small events (Iio, 1992 [8]), medium size shocks (Ellsworth and Beroza, 1995 [4]) and large earthquakes (Umeda, 1992 [12]). A large variety of initial phases have been recognized and it seems difficult to explain all of them with a single initial rupture model. At least two kinds of initial phases have been recognized: A slow emerging phase observed mainly for small earthquakes (Iio, 1992 [8]) and sharp onset (Umeda, 1992 [12]; Ellsworth and Beroza, 1995 [4]) phases. These phases may represent a transition from slow rupture initiation to fast dynamic rupture in source region.

Singh et al. (1998) [11] explained these initial phases based on a cascade model (Ellsworth and Beroza, 1995 [4]). In their model, they assumed that all earthquakes in any size have a pulsive initial phase and in small earthquakes these phases are smoothed due to seismic wave attenuation. They also assume that each cascade event is described by a kinematic model. Using the model, they explained the observation.

Das and Kostrov (1983) [3] studied the break of a single asperity and seismic wave radiation from this rupture. They showed that once initiated rupture propagates around the rim of the asperity and meet on its opposite side. In their computations, they could not analyze in detail the interaction of rupture fronts when they meet because their computation did not have enough spatial resolution. Close scrutiny of the far field displacement function that they computed shows that rupture front interaction can produce large slip velocity pulses. Note that in their model, they

assumed that pre-slip (or post slip of the previous earthquake) occurs outside the asperity.

In this note, we assume that the asperity is close to rupture due to stress concentration on its rim. We compute the stress distribution after quasi-static pre-slip and then, at some arbitrary point on the rim, we assume that a dynamic rupture starts to propagate. We investigate in detail the rupture process around the asperity using a friction model that includes a finite slip weakening zone in order to regularize the rupture front dynamics. The observed radiation complexity is entirely due to the heterogeneity of the initial stress distribution.

We also consider a multi asperity model, where dynamic rupture interaction occurs between the asperities. This model simulates some of the basic features of the cascade model proposed by Ellsworth and Beroza (1995) [4]. Our numerical simulations produces high slip velocities and strong radiation when rupture fronts interact strongly. Our computations include three dimensional effects which have not been completely taken into account in previous studies (Harris and Day, 1993 [6]; Yamashita and Umeda, 1994 [14]; Umeda et al., 1996 [13]). This mechanism can produce high frequency waves with low stress drop or with small moment release.

Method

Let us consider a fault plane in homogeneous unbounded elastic medium. The fault plane is located on the $x_3 = 0$ plane in the Cartesian coordinate (ξ_1, ξ_2, ξ_3) . We follow the method by Fukuyama and Madariaga (1998) [5], which is based on BIEM (boundary integral equation method). In this formulation, stress distribution is linearly related to the slip velocity on the fault surface. Inside the slipping part of the fault we assume a simple triangular slip weakening friction law (Ida, 1972 [7]). The α -component of stress $T_\alpha^{\ell mn}$ and the β -component of slip velocity $V_\beta^{\ell mn}$ at $(\ell\Delta x, m\Delta x, n\Delta t)$ are expressed as follows.

$$T_\alpha^{\ell mn} = -\frac{\mu}{2c_T}V_\alpha^{\ell mn} + \sum_{ij} \sum_{k < n} B_{\alpha\beta}^{ijk\ell mn} V_\beta^{ijk} + \sigma_0^{\ell m} \quad (1)$$

$$T_\alpha^{\ell mn} = \begin{cases} \frac{\sigma_c^{\ell m} - \sigma_f^{\ell m}}{D_c}(\Delta t V_\alpha^{\ell mn} + D_\alpha^{\ell mn}) + \sigma_c^{\ell m} & (\text{if } 0 \leq \Delta t V_\alpha^{\ell mn} + D_\alpha^{\ell mn} < D_q) \\ \sigma_c^{\ell m} & (\text{otherwise}) \end{cases} \quad (2)$$

where

$$D_\alpha^{\ell mn} = \Delta t \sum_{k=0}^{n-1} V_\alpha^{\ell mk} \quad (3)$$

and $B_{\alpha\beta}^{ijk\ell mn}$ is a kernel which has been derived by Fukuyama and Madariaga (1998) [5]. $\sigma_c^{\ell m}$ and $\sigma_f^{\ell m}$ are peak frictional stress (static friction) and final stress, respectively. $\sigma_0^{\ell m}$ is the initial stress at the point $(\ell\Delta x, m\Delta x, 0)$.

Equation (1) represents the boundary condition on the crack, while Equation (2) shows the constitutive relation (or friction law) acting on the crack. Note that $D_\alpha^{\ell mn}$ is constant at time $n\Delta t$.

We study spontaneous rupture propagation by solving Equations (1) and (2) simultaneously at each time step to obtain stress and slip velocity distribution.

Description of the model

We investigate three dimensional effects on the propagation of rupture due to a heterogeneous distribution of initial stress. We consider two models. These models are schematically illustrated in Figure 1.

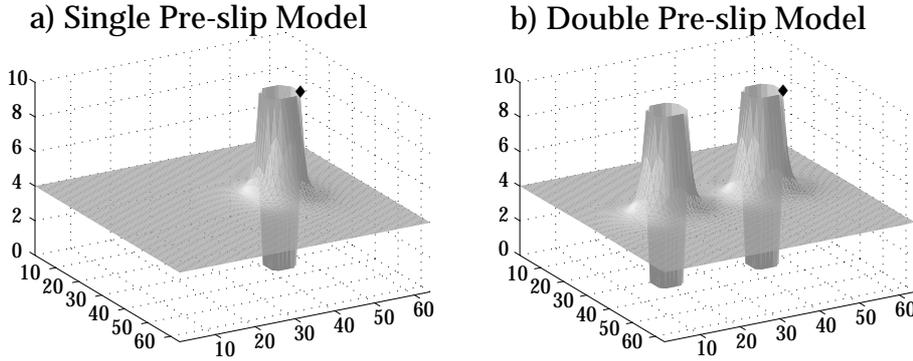


Figure 1: Initial stress (σ_i) distribution for (a) single pre-slip model and (b) double pre-slip model. In both models, critical stress (σ_c) and frictional stress (σ_f) are assumed to be 10 and 0, respectively. Diamonds indicate the rupture starting point where the critical stress is assumed to be slightly below the initial stress.

Single pre-slip model

We assume that an asperity has been formed due to previous earthquakes or to quasi-static pre-slip. Because of the pre-slip, stress is strongly concentrated around the perimeter of the pre-slip region. We define the asperity as the zone of high stress concentration that surrounds the area in which the pre-slip occurred. In this model the initial shear stress at the center of an asperity has been lowered by pre-slip. Stress has been raised by the stress concentration outside the pre-slip area and it decays toward outside the asperity as shown in Figure 1 (e.g. Andrews, 1976 [1]). In this model and hereafter, we assume that critical stress (σ_c) and frictional stress (σ_f) in Equation (2) equal to 10 and 0, respectively. This model has been designed in order to study the three dimensional effects of rupture propagation.

We simulate a dynamic fracture episode that starts some time after the pre-slip process. We assume that the dynamic fracture initiates at some point along the rim of asperity, and that rupture propagates spontaneously under the control of slip weakening friction. We assume that after the pre-slip strength recovered completely before dynamic rupture starts.

Double pre-slip model

In this model, we assume that pre-slip occurs in several places on the fault and that these pre-slip patches are surrounded by static stress concentrations. The stress concentration around each asperity has the same stress concentration as in the single asperity model. Other, more complex stress distributions can of course be considered,

but we want to study focusing effects due to inhomogeneous stress distributions deduced from simple pre-slip fields.

At some point on the rims of one of the asperities, a rupture process starts dynamically. It breaks the rim of the first asperity, then rupture progresses outside this asperity and approaches the stress concentrations around other asperities. Since elastic wave propagate faster than the rupture front, the other asperities start to break due to stress perturbations produced by the elastic waves emitted by the rupture front of the first asperity.

In order to emphasize the qualitative features of our model, we show results only for two asperities, although it is not difficult to extend our computations to more general multi-asperity models.

Results of computation

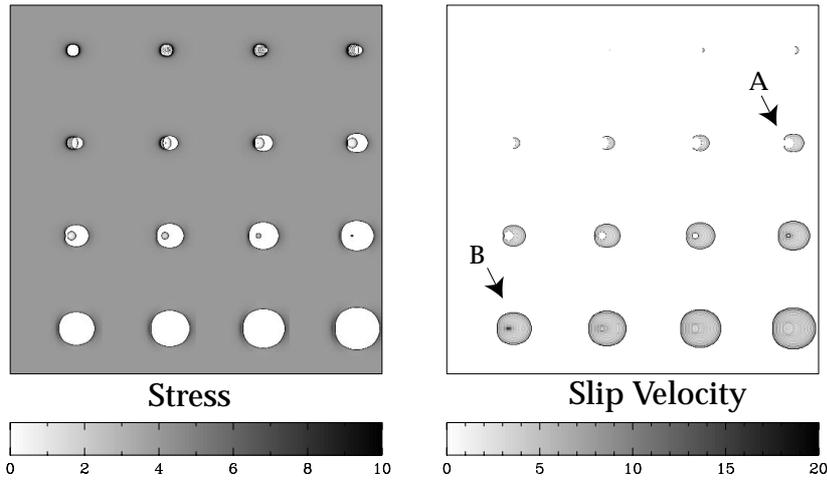
In a single pre-slip case, as shown in Figure 2a, rupture propagates following closely the area of stress concentration around the rim of the initial slip zone. After moving around the asperity as proposed by Das and Kostrov (1983) [3], the two rupture fronts meet with each other at the opposite side of the asperity with respect to the initiation point (A in Figure 2a). At that time a very high slip velocity concentration occurs. After this focusing phenomenon, rupture propagates beyond the asperity and also towards the center of the of the asperity. Inside the asperity the pre-slip zone starts to move until the rupture front concentrates near the center of the asperity (B in Figure 2a). At this point, very high slip velocities are observed at the center of the crack.

This effect is due to the rupture front focusing. If the rupture front focuses, stress concentration in front of the rupture increases and then rapid stress drop occurs. This high stress drop produces in turn very high slip velocities. In two dimensions, this kind of rupture focusing can only occur when two isolated ruptures connect with each other (Das and Aki, 1977 [2]). However, in three dimensions, we emphasize that rupture focusing, and high slip rates, can occur even if rupture starts at a single point.

In a more realistic situation several asperities may exist and one of them starts to break. As shown in Figure 2b, the rupture process is initially very similar to the single asperity case until the second asperity starts to break. This second break occurs before the rupture front reaches the asperity triggered by the elastic wave emitted from the initial rupture (C in Figure 2b). After that, the two ruptures grow separately until they connect with each other. At this point slip velocity becomes very strong (D in Figure 2b). This is because in three dimension, the two ruptures interfere along an elongated zone with certain time delay. So that the zone of high slip velocities becomes bigger compared to the previous case and emits the strongest high frequency waves. Finally, the remained area inside the pre-slip zone disappears (E in Figure 2b).

We also computed seismic ground velocities using the representation theorem by integrating slip velocity on the fault and taking a time derivative. In Figure 3, Far field signals have several peaks (A - E in Figure 3), each of which corresponds to one of the high slip velocity zones created by focusing (Figure 2ab).

a) Single Pre-slip Model



b) Double Pre-slip Model

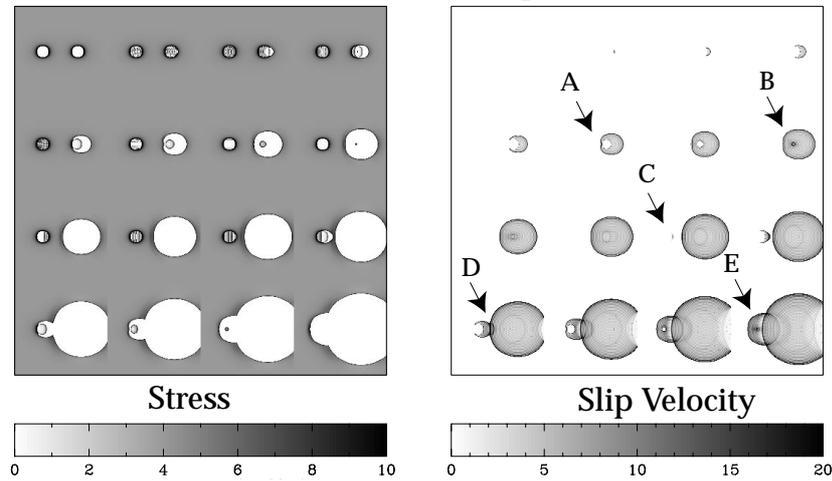


Figure 2: a) Result of computation for single pre-slip model. Left panel shows stress distribution time snapshot and right is slip velocity snapshot. Time passes from left top to rightward and then downward with equal time step ($10\Delta t$). b) Result of computation for double pre-slip model. Left panel shows stress distribution time snapshot and right is slip velocity snapshot. Time passes from left top to rightward and then downward with equal time step ($16\Delta t$).

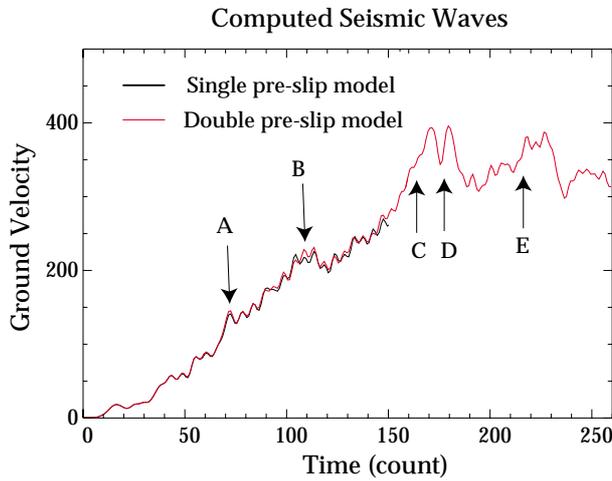


Figure 3: Seismic ground velocities observed at far distance for single and double pre-slip models. A - E correspond to the snap shots in Figure 2.

Discussion and conclusion

We have demonstrated that rupture process are strongly guided by the pre-stress field on a fault. The pre-stress produces segmented rupture fronts that propagate following very closely the zones of stress concentration. In the case of a single asperity, rupture surrounds the asperity as proposed by Das and Kostrov (1983) [3] and produces very strong radiation when the two rupture zones that follow the stress concentration meet at the opposite side of the asperity edge. This mechanism could be a origin of seismically observed initial phase of large earthquakes.

If we assume that pre-slip size is proportional to the size of the earthquake as suggested by Ohnaka (1993) [9] and Shibazaki and Matsu'ura (1998) [10], amplitudes and time delays of the high frequency wave also become proportional to the earthquake size. Moreover, in large earthquakes, asperities are likely to be more densely distributed than for smaller earthquakes. Thus in large earthquakes high frequency waves are easy to emit at the initial stage.

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