Numerical simulation of seismic cycles at a subduction zone with a laboratory-derived friction law

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Abstract

We review recent studies of numerical modeling of seismic cycles at subduction zones in Japan. Laboratory-derived rate- and state-dependent friction laws are most useful for modeling the entire seismic cycles including aseismic sliding and healing. Among several versions of the rate- and state-dependent law, the composite law better fits experimental observations for a wide range of conditions and is most apropriate for application to modeling of seismic cycles. Models for the Tokai earthquake, which is expected to occur in a seismic gap along the Suruga trough, central Japan, predict that accelerating preseismic sliding occurs. We propose a model for aseismic episodic slip events, which have been detected around the Japanese islands with GPS observations.

Introduction

Laboratory-derived rate- and state-dependent friction laws developed by Dieterich [1] and Ruina [2] are useful for modeling of seismic cycles because they adequately take into consideration some important property of rock friction such as rate- and slip-dependence of frictional strength and time-dependent restrengthening, and they well explain various experimental observations in laboratories. Tse and Rice [3] applied the friction law to modeling of seismic cycles of a vertical strike-slip fault, and Stuart [4] modeled seismic cycles at the Nankai trough subduction zone, southwestern Japan. Since these models may quantitatively describe some important geophysical phenomena such as the variation with depth of seismic slip, postseismic slip and preseismic slip, the simulation results can be directly compared with seismic and geodetic data. Moreover, if we have detailed spatial distribution of friction parameters on a plate boundary, we may forecast sliding behavior on the plate boundary. To this end, an exact friction law is necessary. We review recent studies of an improvement of the friction law and of numerical models of seismic cycles at subduction zones in Japan. We briefly describe a research plan for more realistic model with the "Earth Simulator".

Composite rate- and state-dependent friction law

There exist several versions of rate- and state-dependent friction law. Although their characteristics are similar to one another, the difference is significant for quantitative models of seismic cycles. We review in this section the most widespread versions, the slowness law and the slip law, of the friction law, and a newly introduced one, the composite law, by Kato and Tullis [5].

According to, for instance, Ruina [2], the frictional stress τ following a rate- and state-dependent friction law is given by

$$\tau = \mu \, \sigma_n^{eff}, \quad (1)$$

$$\mu = \mu_* + a \ln(V/V_*) + b \ln(V_* \theta / L), \quad (2)$$

where μ is a friction coefficient, σ_n^{eff} is an effective normal stress, V is a sliding velocity, θ is a state variable representing a contact state of sliding surfaces or an internal structure of a fault gouge zone, and a, b and L are constants. V_* is an arbitrarily chosen reference velocity, and μ_* is a reference friction coefficient dependent on V_*.

The evolution of the state variable expresses the time- and displacement-dependent effects on friction, and is written by

$$d\theta/dt = 1 - \theta \, V/L, \quad (3)$$

in the slowness law,

$$d\theta/dt = -(\theta V/L) \ln (\theta V/L), \quad (4)$$

in the slip law, and

$$d\theta/dt = \exp(-V/V_c) - (\theta V/L) \ln(\theta V/L), \quad (5)$$

in the composite law, where Vc is a constant. The slowness law better explains the healing process at very small sliding velocities than the slip law, and the slip law better fits the experimental observation about frictional behavior around steady-state sliding. The composite law was developed by Kato and Tullis [5] to obtain a new law that has the advantages of both the slowness law and the slip law.

Kato and Tullis [6] compared the three friction laws by numerical simulation of great interplate earthquake cycles at a subduction zone to find that there is significant difference in the simulated seismic cycles. Using the same values of the friction parameters, Kato and Tullis [6] found that the recurrence interval and coseismic slip are the largest for the composite law, and the magnitude of preseismic sliding is the largest for the slowness law. Thus the selection of friction law is important in modeling seismic cycles.

Models for the Tokai earthquake

Earthquakes of magnitude 8 class have repeatedly occurred at intervals of 90 to 150 years along the Nankai and the Suruga trough, southwestern Japan, and there is a seismic gap in the easternmost section of this region (Ishibashi [7]).

Kato and Hirasawa [8] presented a model for the Tokai earthquake, applying the rate- and state-dependent friction law, to evaluate possible preseismic crustal deformation and stress variation due to aseismic sliding. Their model predicts that the stress variation may change seismicity rate and forcal mechanisms of intraplate small earthquakes around the expected source area of the Tokai earthquake. They compared the simulated preseismic strain with the noise levels of borehole strainmeters installed in the Tokai region by Japan Meteorological Agency. Kuroki et al. [9] improved the model by Kato and Hirasawa [8] by introducing more realistic 3-D curved configuration of plate boundary to obtain smaller amplitudes of preseismic crustal deformation.

Mechanism of aseismic episodic slip events

Recently, a significant slow episodic strain event was observed in the Tokai region with GPS. Ozawa et al. [10] analyzed GPS data obtained for many stations in the Tokai district to find that the strain event can be explained by a slow slip event on the plate boundary near the expected source area of the Tokai earthquake. Similar slow strain events were observed with GPS around the Japanese islands. A typical example is a slow slip event in the Bungo channel region, southwestern Japan. Hirose et al. [11] showed that this significant crustal deformation may be explained by slow slip on the plate boundary with the duration of about 10 months and the moment magnitude of 6.6.

These slip events may easily be explained by the rate- and state-dependence of rock friction. For a single-degree-of-freedom spring-block system, where the friction on the block base obeys a rate- and state-dependent law, the critical stiffness k_c [2] can be defined by

$$k_c = (b\text{-a})\ \sigma_n^{eff}/L. \tag{6}$$

When the spring stiffness is smaller than k_c, seismic slip may take place, when the stiffness is larger than k_c, stable sliding occurs, and when the stiffness is nearly equal to k_c, episodic sliding may occur. For a finite fault in an elastic medium, an effective stiffness k^{eff} of a fault may be defined by

$$k^{eff} = \Delta\tau/\Delta u. \tag{7}$$

where $\Delta\tau$ is the stress change due to slip Δu on the fault. For a circular shear crack with a constant stress drop, k^{eff} is given by

$$k^{eff} = (7\pi\ /24)(G/r), \tag{8}$$

where G is rigidity and r is a fault radius. From (6) and (8), the critical fault radius r_c can be defined by

$$r_c = (7\pi\ /24)\ [GL/(b\text{-a})\ \sigma_n^{eff}]. \tag{9}$$

When the fault dimension is nearly equal to the critical fault size, an episodic slip event is expected to occur.

To confirm this idea, we perform a numerical simulation. We consider a 2D planar fault in an infinite uniform elastic medium. The frictional stress acting on the fault is assumed to obey a composite rate- and state-dependent friction law, and the fault plane is assumed to slip in the x-direction with a slip rate V_{pl} on the average. Figure 1 shows an example model fault, where a circular patch of the radius r = 3 km with $(a\text{-}b)\sigma_n^{eff}$ = -0.2 MPa is embedded, while $(a\text{-}b)\ \sigma_n^{eff}$ = 0.2 MPa on the outside of the patch. The characteristic slip distance L is 5 cm uniform over the fault. The critical fault radius r_c is calculated from (9) to be 4.12 km, and then the patch size is a little smaller than the critical size (r/r_c = 0.73). Figure 2 shows simulated slip histories during the entire cycle at 8 points on the fault. Rapid slip occurs at Points 7 and 8, which are inside the negative *a-b* patch. Since the rise time of the slip is on the order of 10 days, this event is not an earthquake but an aseismic episodic slip event. The slip rise time for the points in the positive *a-b* region tends to be long with the distance from the negative *a-b* patch. We perform a lot of simulations with various values of model parameters. In addition to the nonunifromity of *a-b*, aseismic episodic slip events are generated with nonuniformity in the effective normal stress σ_n^{eff} or in the characteristic slip distance *L*, if the patch size is comparable with the critical fault size. The duration of the simulated episodic slip events tends to be long with a decrease in r/r_c . This may be used for estimating friction parameters on the plate boundary from the estimated fault size and source duration of observed episodic slip events. It is noted that an aseismic episodic event may be simulated in more realistic subduction zone models, when nonuniformity in friction parameters is introduced [12].

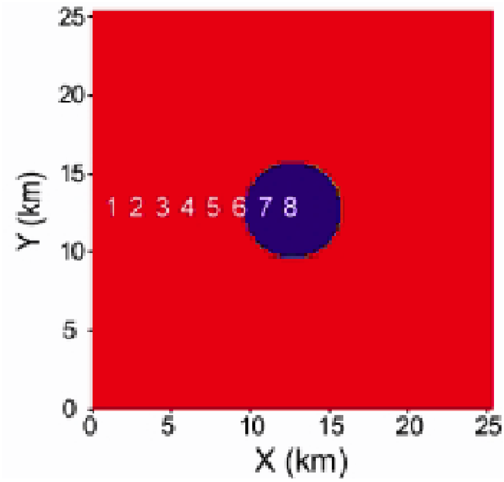

Figure 1: Spatial distribution of *(b-a)* σ_n^{eff} assumed on the 2-D model fault. The numerals 1 to 8 are the points where slip histories are displayed in Figure 2.

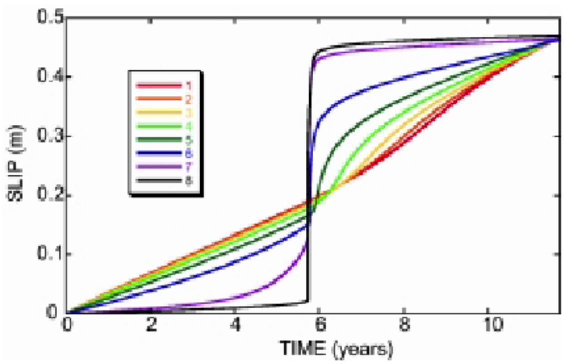

Figure 2: Simulated slip histories at 8 points on the fault during the entire cycle.

Concluding remarks

Modeling of seismic cycles at subduction zones with rate- and state-dependent friction laws successfully explains various phenomena such as preseismic sliding, postseismic sliding, and aseismic episodic slip events. However, the present models are too simple to simulate realistic complicated earthquake sequences such as those observed along the Nankai trough, southwestern Japan, where large earthquakes occurred quasi-periodically and the source areas varied [8]. To simulate this complicated behavior, the effects of stress changes due to slip on neighboring segments on a plate boundary and intraplate earthquakes must be taken into consideration. Further, for more realistic models, we must take into consideration heterogeneity of elastic and viscoelastic property of crust and upper mantle, which may significantly affect large-scale stress concentration and long-term crustal deformation. To deal with heterogeneous viscoelastic structure, we will adopt FEM technique in future research with the "Earth Simulator" [13].

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