Three dimensional simulation for the earthquake cycle at a subduction zone based on a rate- and state-dependent friction law: Insight into a finiteness and a variety of dip-slip earthquakes

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Abstract

Three dimensional numerical simulations for the earthquake cycle at a subduction zone are carried out in order to explore the earthquake generation process and try to reproduce a wide variety of slip behaviors. Our quasi-static simulation in an elastic medium includes a laboratory derived rate- and state-dependent friction law. We examine the effect on the slip behavior of model dimension in strike direction relative to the seismogenic zone width. In cases with the strike dimension comparable to the seismogenic zone width, an earthquake occurs periodically with a characteristic magnitude. The focus of the earthquake is centered in the strike direction. In contrast, for cases with a much larger strike dimension, earthquakes initiate at various locations on the fault. No characteristic earthquake magnitude is observed. Our model provides one possible mechanism for arresting rupture propagation and can generate a variety of earthquake slip behaviors.

Introduction

Slip behaviors on a plate interface at subduction zones have a wide variety of styles: periodic large earthquakes, tsunami earthquakes [1], afterslip following ordinary earthquakes [2], slow slip events [3, 4], and so on. It is important to understand slip behavior during the whole earthquake cycle, in order to explore the mechanisms that control earthquake generation processes in subduction zones.

Numerical simulation studies of the earthquake cycle at subduction zones has been carried out by Stuart [5] and Kato and Hirasawa [6, 7]. Their models are based on a laboratory derived rate- and state-dependent friction constitutive law [8, 9]. Their models are two dimensional, leading to an implicit assumption of infinite fault length in the strike direction. Recently, Kuroki et al. [10] constructed a three dimensional model including a configuration of the subducted plate interface to simulate the future Tokai earthquake along the Suruga trough, in central Japan. However, they did not evaluate what features are intrinsic in three dimensional simulation. We believe that it is important to understand the generic behavior of this system for a simpler case.

We therefore develop a 3-D simulation code, where slip can propagate not only in the dip direction but also in the strike direction, extending the 2-D model of

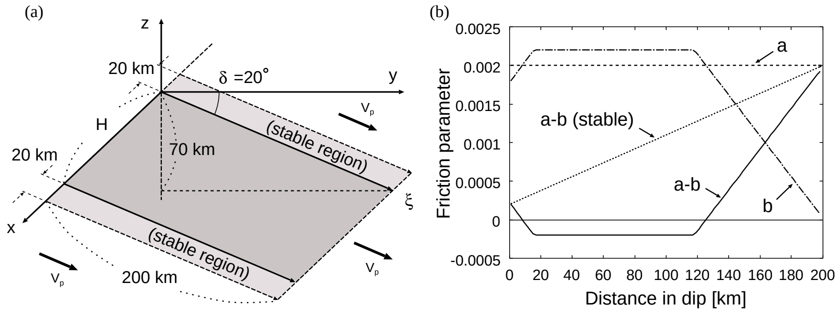

Figure 1: (a) Simulation model geometry and coordinate system definition. ξ is a distance from a trench in dip direction. (b) Distribution of friction parameter a, b, and $a-b$ with respect to depth. $a-b$ of the outermost stable region (the line labeled '$a-b$ (stable)') is also plotted.

Kato and Hirasawa [6]. We do not include the configuration of the plate interface, i.e., we only model a planar fault. Then we determine the effect of model dimension in a lateral direction on the slip behavior of a subducting plate.

Simulation method

We developed a 3-D model based on [6]. Our model consists of a planar thrust fault in an elastic half-space (Fig. 1a). Our model has the same dip angle (20°) and fault width in dip direction (200 km) as the 2D model of [6], to allow for comparison. We examine the effect of changing the fault length (H).

The fault plane is discretized into a large number of small square cells, with dimensions 2 km × 2 km. We take only a dip-slip component into account in both slip and stress. At each cell, the quasi-static shear stress balance can be written as

$$\tau_i = \sum_j K_{ij}(V_p t - u_j) - \eta V_i, \tag{1}$$

where V_p is the driving velocity and is assumed to be 10 cm/yr. To calculate the static Green's function term (K_{ij}), we use the analytical expression given by Okada [11]. Frictional stress acting on these cells is assumed to obey a rate- and state-dependent friction law [8, 9]. The frictional stress τ is written by

$$\tau = \mu\sigma^{\text{eff}}, \tag{2}$$

$$\mu = \mu_0 + a\ln(V/V_p) + b\ln(\theta V_p/L), \tag{3}$$

$$\frac{d\theta}{dt} = 1 - \frac{\theta V}{L}. \tag{4}$$

We also include the velocity cutoff in the steady state frictional strength, μ^{ss}, where μ^{ss} becomes independent of V above 0.1 mm/s [12]. A distribution of the friction parameters a and b with respect to depth is shown in Fig. 1b. L is taken as 5 cm. These values are the same as those in case 1 of [6].

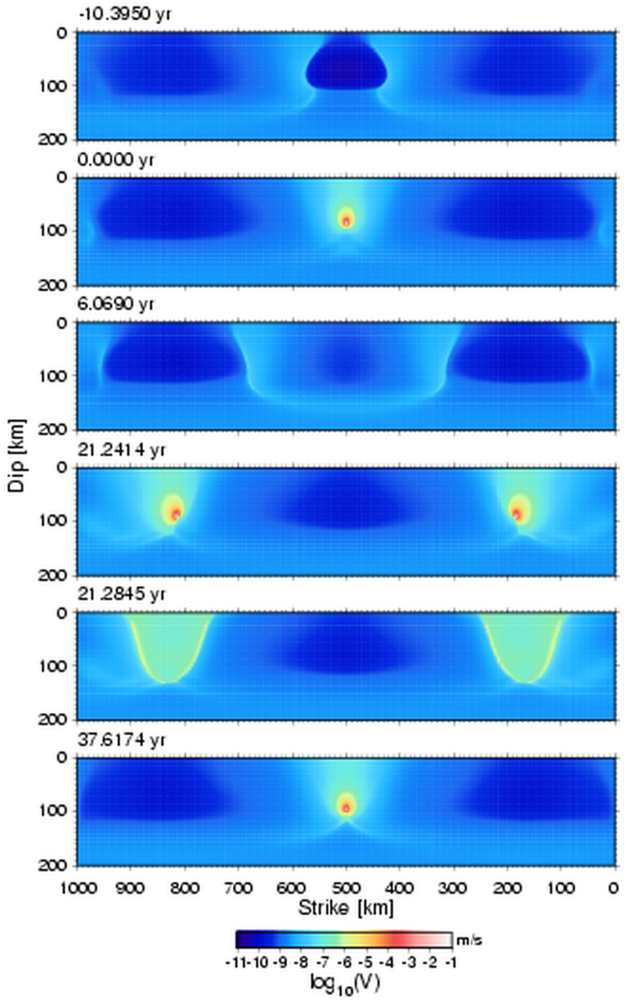

Figure 2: Snapshots of slip velocity with H =1000 km.

Results

We performed numerical simulations for several cases with H values ranging from 200 km to 1200 km. General behaviors are as follows: (1) aseismic slip propagates from stable sliding regions into the unstable slipping region with $a - b < 0$ (we call this propagating aseismic slip 'preslip'); (2) fast slip events, or earthquakes, occur at the point where such preslips meet each other; (3) fast slip propagates to a surrounding area with decreasing sliding velocity ('afterslip').

In cases with $H \leq 400$ km, earthquakes with the same magnitude recurred periodically, centered in the strike direction. This regular periodic behavior is similar to the result of 2-D model [6] except that the event time interval is shorter and the magnitude is smaller. On the other hand, in cases with $H \geq 500$ km, earthquakes

occur not only in the center but also in the area near the edges, or other positions (Fig. 2). These recurrence intervals are not at constant times in each seismic cycle or locations on the fault surface. Moreover, magnitudes vary between each event.

This transition of the slip behavior from regular to complex with increasing H is mainly due to the propagation of preslips in both strike and dip directions. The propagating preslips are caused by a stress concentration at the border between the unstable slipping region and the steady sliding region. When H is smaller than a certain 'critical' size, H_c, the seismic cycles are dominated by the slip propagation in the lateral direction because the lateral propagation velocity is faster than that in the dip direction. On the other hand, when H is larger than H_c, lateral slip propagation is no longer dominant, and some of the longitudinally propagating preslips meet earlier than the laterally propagating ones. Note that H_c is expected to depend on the friction parameter distribution, so that more simulations are required for discussing the dependency of H_c on the friction parameters.

Discussion

Our results with larger H show that there are events which cannot break the whole seismogenic zone. From another point of view, we can see that the propagating rupture front arrests spontaneously. The slip events also occur at positions other than the center so that the shear stress is heterogeneously distributed. In addition, shear stress at the propagating rupture front decreases with increasing coseismic rupture area. Both of these factors contribute to the arrest of rupture.

Although our model is a continuum one, as discussed by Rice [13], it has the potential to produce a certain variety of earthquake slip behaviors. Indeed, we observe several 'slow slip events,' meaning temporal events with slower maximum sliding velocities. As we mentioned above, slip events which do not rupture the whole seismogenic region also occur in our model. In the area that has slipped more time is needed to accumulate stress than in the unslipped region. A subsequent slip event occurs at this unslipped region. During the next event, it is difficult for the rupture to propagate through the previously slipped area. Accordingly, the size of the unbroken region at the previous event defines the dimension of the following slip event. Dieterich [14] shows that a fault must have a critical fault dimension, l_c, for unstable slip to occur. Our results imply that the dimension of the unbroken region relative to l_c defines the stability of the next slip event.

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References

[1] Kanamori, H., and Kikuchi, M., 1993, *The 1992 Nicaragua earthquake: a slow tsunami earthquake associated with subducted sediments,* Nature, **361**, 714–716.

[2] Heki, K., Miyazaki, S., and Tsuji, H., 1997, *Silent fault slip following an interplate thrust earthquake at the Japan Trench,* Nature, **386**, 595–598.

[3] Hirose, H., Hirahara, K., Kimata, F., Fujii, N., and Miyazaki, S., 1999, *A slow thrust slip event following the two 1996 Hyuganada earthquakes beneath the Bungo Channel, southwest Japan,* Geophys. Res. Lett., **26**, 3233–3236.

[4] Ozawa, S., Murakami, M., and Tada, T., 2001, *Time-dependent inversion study of the slow thrust event in the Nankai trough subduction zone, southwestern Japan,* J. Geophys. Res., **106**, 787–802.

[5] Stuart, W. D., 1988, *Forecast model for great earthquakes at the Nankai trough subduction zone,* Pure Appl. Geophys., **126**, 619–641.

[6] Kato, N., and Hirasawa, T., 1997, *A numerical study on seismic coupling along subduction zones using a laboratory-derived friction law,* Phys. Earth Planet. Inter., **102**, 51–68.

[7] Kato, N., and Hirasawa, T., 1999, *A model for possible crustal deformation prior to a coming large interplate earthquake in the Tokai district, central Japan,* Bull. Seism. Soc. Am., **89**, 1401–1417.

[8] Dieterich, J. H., 1979, *Modeling of rock friction, 1, Experimental results and constitutive equations,* J. Geophys. Res., **84**, 2161–2168.

[9] Ruina, A., 1983, *Slip instability and state variable friction laws,* J. Geophys. Res., **88**, 10,359–10,370.

[10] Kuroki, H., Ito, H., and Yoshida, A., 2001, *Earthquake cycle modeling and the Tokai Earthquake (in Japanese),* Chikyu Monthly, Extra, **33**, 139–145.

[11] Okada, Y., 1992, *Internal deformation due to shear and tensile faults in a half-space,* Bull. Seism. Soc. Am., **82**, 1018–1040.

[12] Tse, S. T., and Rice, J. R., 1986, *Crustal earthquake instability in relation to the depth variation of frictional slip properties,* J. Geophys. Res., **91**, 9452–9472.

[13] Rice, J. R., 1993, *Spatio-temporal complexity of slip on a fault,* J. Geophys. Res., **98**, 9885–9907.

[14] Dieterich, J. H., 1986, *A Model for the Nucleation of Earthquake Slip,* In *Earthquake Source Mechanics,* (Das, Boatwright, Scholz, eds.), Geophys. Monogr., 37, American Geophysical Union, 37–47.