

Physical modelling of earthquake generation cycles at transcurrent plate boundaries

Chihiro Hashimoto⁽¹⁾ and Mitsuhiro Matsu'ura⁽¹⁾

(1) Department of Earth and Planetary Science, The University of Tokyo, Tokyo, Japan
(e-mail: hashi@solid.eps.s.u-tokyo.ac.jp; matsuura@eps.s.u-tokyo.ac.jp, phone: +81-3-5841-4652; +81-3-5841-4318).

Abstract

We have constructed a 3-D physical model of earthquake generation cycles at transcurrent plate boundaries by incorporating the slip- and time-dependent fault constitutive law into the quasi-static tectonic loading model. With this model we have numerically simulated the entire process of earthquake generation and revealed the evolution of fault constitutive properties during a complete earthquake cycle. In this model the fault strength decreases with fault slip and increases with stationary contact time. After the arrest of dynamic rupture, the restoration of the peak strength σ_p proceeds rapidly. On the other hand, the restoration of the critical weakening displacement D_c proceeds gradually with time through the interseismic period. These results give a theoretical explanation for observational facts of the event-scale dependence of D_c .

Introduction

Earthquake generation cycles at plate boundaries can be regarded as a process of tectonic stress accumulation and release, resulting from relative plate motion. The basic equations governing this process are a viscoelastic slip response function, a fault constitutive relation, and a steady relative plate motion as a driving force. For example, with the rate- and state-dependent type of constitutive laws proposed by Dieterich [1] and Ruina [2], Tse and Rice [3], Stuart [4] and Kato and Hirasawa [5] have developed 2-D earthquake generation cycle models. With the slip-weakening type of constitutive law derived by Matsu'ura et al. [6], Hashimoto and Matsu'ura [7] have constructed a 3-D physical model of tectonic loading at transcurrent plate boundaries. However, this model can not treat earthquake generation cycles, because the simple slip-weakening constitutive law has no inherent mechanism of strength restoration. In the present study, we extend our tectonic loading model to an earthquake generation cycle model by incorporating the slip- and time-dependent fault constitutive law proposed by Aochi and Matsu'ura [8]. The slip- and time-dependent law defines the evolution of shear strength with fault slip and contact time. The essential parameters controlling this constitutive law are the abrasion rate and the adhesion rate.

A physical model of earthquake generation cycles

First we consider an elastic surface layer overlying a Maxwellian viscoelastic half-space as a model of the lithosphere-asthenosphere system. The elastic surface layer is divided into two blocks by an infinitely-long vertical interface. Interaction between these two blocks is simply represented by the increase of tangential displacement discontinuity (fault slip) across the interface.

We decompose the fault slip w into the steady plate motion at a constant rate v_{pl} and its perturbation u_s :

$$w(\mathbf{x}, t) = v_{pl}t + u_s(\mathbf{x}, t). \quad (1)$$

The shear stress σ due to the fault slip w is calculated by the hereditary integral of the internal viscoelastic stress function $H(\mathbf{x}, t; \boldsymbol{\xi}, \tau)$ to a unit step slip on the plate boundary:

$$\sigma(\mathbf{x}, t) = \sigma_0(\mathbf{x}) + \int_0^t \int_{\Sigma_s} \frac{\partial u_s(\boldsymbol{\xi}, \tau)}{\partial \tau} H(\mathbf{x}, t - \tau; \boldsymbol{\xi}, 0) d\boldsymbol{\xi} d\tau, \quad (2)$$

where the first and the second terms indicate the contributions from the steady plate motion and the slip perturbation, respectively. The concrete expression of $H(\mathbf{x}, t; \boldsymbol{\xi}, \tau)$ has been obtained by Hashimoto and Matsu'ura [7]. In the present problem the distribution of fault slip w is unknown. What we know is the fault constitutive relation that defines the shear strength σ_{strg} as a function of fault slip w and contact time t . Then we give a stress boundary condition on the plate interface as

$$\begin{cases} \sigma(\mathbf{x}, t) \leq \sigma_{strg}[w(\mathbf{x}, t), t; \mathbf{x}] & (dw/dt = 0) \\ \sigma(\mathbf{x}, t) = \sigma_{strg}[w(\mathbf{x}, t), t; \mathbf{x}] & (dw/dt > 0) \end{cases}, \quad (3)$$

The physical process of earthquake generation cycles is essentially governed by the coupled nonlinear equations (1), (2) and (3).

As to the fault constitutive relation, Aochi and Matsu'ura [8] have theoretically derived the expression of shear strength σ_{strg} as a function of w and t in the following form of wavenumber (k) integral:

$$\sigma_{strg}(w, t) = \sigma_0 + c \left[\int_0^\infty k^2 |Y(k; w, t)|^2 dk \right]^{1/2} \quad (4)$$

with

$$\begin{aligned} d|Y(k; w, t)| &= -\alpha k |Y(k; w, t)| dw \\ &+ \beta k^2 \left[|\bar{Y}(k)| - |Y(k; w, t)| \right] dt, \end{aligned} \quad (5)$$

where $|Y|$ and $|\bar{Y}|$ are the Fourier component of fault surface topography and its maximum restorable value, respectively. The abrasion rate α and the adhesion rate β are the position-dependent parameters, prescribing physical properties of fault surface. Given the values of α and β and a slip history on the fault, we can calculate the values of $\Delta\sigma_p$ (breakdown strength drop) and D_c (critical weakening displacement) at every moment.

Results of numerical simulation

Figure 1 shows a series of snapshots for the stress accumulation and release during an earthquake cycle. The relative plate velocity v_{pl} is taken to be 5 cm/yr. Then the process of stress accumulation and release is repeated with the recurrence interval of about 26 yr. The average stress drop at the seismic event, evaluated from the stress distribution just before the unstable rupture, is about 1.8 MPa.

The fault constitutive parameters, $\Delta\sigma_p$ and D_c , change with fault slip w and stationary contact time t . Figure 2 shows the evolution of fault constitutive relation during one complete earthquake cycle in Figure 1. After the arrest of dynamic rupture, the restoration of $\Delta\sigma_p$ proceeds rapidly. On the other hand the restoration of D_c proceeds gradually with time through the interseismic period.

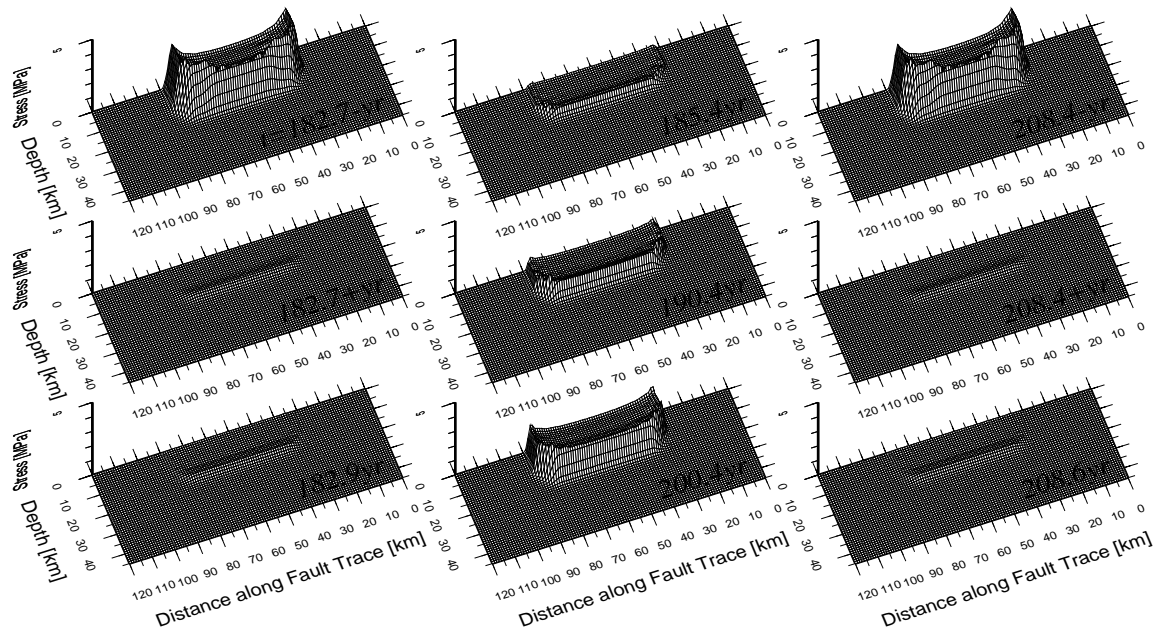


Figure 1: A series of snapshots showing the stress accumulation and release during an earthquake cycle. in the 60 km-long seismogenic region. The process of stress accumulation and release is repeated with the recurrence interval of about 26 yr.

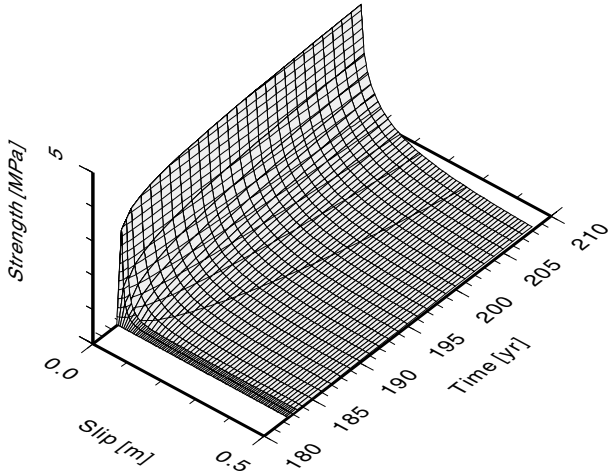


Figure 2: The evolution of fault constitutive relation during one complete earthquake cycle.

We can easily extended the single fault model to the case of multi-segmented fault systems. Figure 3 shows the process of earthquake generation cycles for a fault system consisting of small (30 km) and large (50 km) fault segments separated by the 10 km-long creep section. Stress accumulation proceeds in both segments. First the smaller segment becomes unstable. The elastic stress transfer associated with the rupture of the smaller segment doesn't directly trigger the rupture of the larger segment. The subsequent viscoelastic stress transfer accelerates the stress accumulation in the larger segment. Then, after about 2 yr, the larger segment becomes unstable.

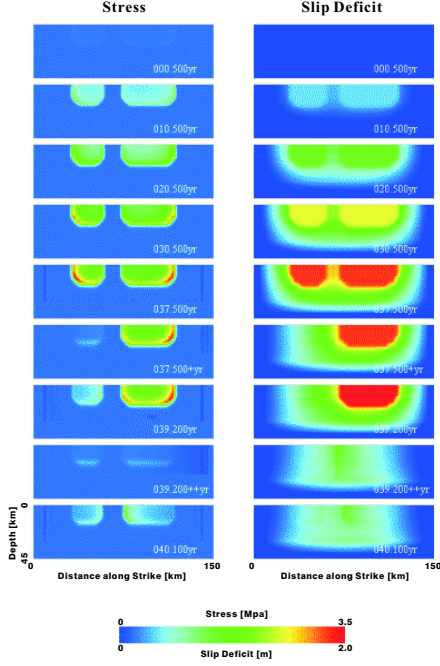


Figure 3: A series of snapshots showing the stress accumulation and release for the 90 km-long fault system with small (30 km) and large (50 km) seismogenic segments. First the smaller segment becomes unstable. The rupture of the smaller segment accelerates the stress accumulation in the larger segment through elastic and viscoelastic stress transfer. Then, after about 2 yr, the larger segment becomes unstable.

Discussion and Conclusions

We constructed a 3-D physical model of earthquake generation cycles at transcurrent plate boundaries. With this model we simulated the entire process of earthquake generation and revealed the evolution of fault constitutive properties during the earthquake cycle. At the time of dynamic rupture the shear strength decreases with fault slip. After the arrest of dynamic rupture, the peak strength is restored rapidly. On the other hand the restoration of the critical weakening displacement D_c proceeds gradually with time through the interseismic period. Matsu'ura et al. [6] and Ohnaka [9] have indicated the linear dependence of D_c on the inverse of the critical wavenumber k_c in roughness of fault surfaces (the upper corner wave-length, $\lambda_c = 2\pi/k_c$, in the power spectrum of fault surface topography). In the present model the value of k_c is process-dependent; the inverse of k_c decreases with fault slip and increases with stationary contact time. The gradual increase of D_c through the interseismic period gives a theoretical explanation for the observational facts of event-scale dependence of D_c pointed out by Aki [10], Ohnaka [9] and Shibazaki and Matsu'ura [11].

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