Simulation of Earthquake Rupture Transition From Quasi-static Growth to Dynamic Propagation

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Abstract

We have simulated a rupture transition from quasi-static growth to dynamic propagation using the boundary integral equation method. In order to make a physically reasonable model of earthquake cycle, we have to evaluate the dynamic rupture propagation in the context of quasi-static simulation. We used a snapshot of the stress just before the earthquake in the quasi-static simulation. And the resultant stress will be feedbacked to the quasi-static simulation. Since the quasi-static simulation used the slip and state dependent friction, friction law itself evolves with time. Thus we used the constitutive relation for dynamic rupture propagation consistent with that used for the quasi-static simulation. We modeled the San Andreas type strike slip fault, in which two different size asperities existed.

Introduction

In order to simulate earthquake cycle in more realistic way, both stress accumulation and release processes are important. Hashimoto and Matsu'ura (2000)[5][6] investigated the stress accumulation process at a transcurrent plate boundary using a two-layered model consisting of the elastic lithosphere and viscoelastic asthenosphere. That enables us to obtain the initial stress distribution just before the earthquake as well as the constitutive relation during the dynamic rupture. On the other hand, the boundary integral equation method (BIEM) was developed in order to compute dynamic rupture propagation on the fault (Fukuyama and Madariaga, 1995[3], 1998[4], Aochi et al., 2000)[2]). BIEM enables us to introduce exactly the constitutive relation on the fault and to compute the dynamic rupture propagation with enough accuracy. By combining these two techniques, we are able to compute a complete earthquake cycle, in which stress accumulation and release processes are properly taken into account.

In this paper, we estimated the stress release during the dynamic rupture by using BIEM (Fukuyama and Madariaga, 1998[4]) in order to make the quasi-static simulation (Hashimoto and Matsu'ura, 2000[5][6]) of earthquake cycle more physically reasonable. And we discuss the initiation of the rupture, which is not always well described in the quasi-static simulation.

Analysis

In order to obtain the initial stress distribution, we used the method by Hashimoto and Matsu'ura (2000)[5][6]. We set up the two layered structure model in which elastic lithosphere

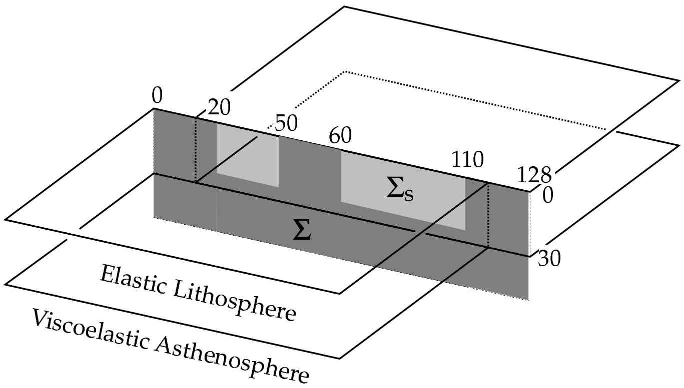

Figure 1: Schematic illustration of the model. The strike-slip type fault is embedded in the elastic lithosphere overlying the viscoelastic asthenosphere. Two kinds of region are assumed: creep region (Σ) and asperity region (Σ_s). The total length and width of the fault is assumed to be 128km and 32 km, respectively. The thickness of the lithosphere is 30km. Outside the fault zone, slip rate is assumed to be constant at the plate velocity (5cm/year).

Table 1: The structural parameters used in numerical computations.

	ρ $[kg/m^3]$	λ $[GPa]$	μ $[GPa]$	η $[Pa \cdot s]$
Lithosphere	3000	40	40	∞
Asthenosphere	3400	90	60	10^{19}

is lied on the visco-elastic asthenosphere as shown in Figure 1. Inside the elastic lithosphere, we put a vertical strike slip fault whose length and width are $128km$ and $32km$, respectively. On the fault we set two different types of region, creep region (Σ) and asperity region (Σ_s), by giving different physical properties of fault surface. In the creep region, stress is not accumulated because of the low adhesion rate. On the other hand, in the asperity region, stress is accumulated in the interseismic period and is released during the earthquake because of the high adhesion rate. The shear strength of the fault σ is defined in the following constitutive relation proposed by Aochi and Matsu'ura, 1999[1].

$$\sigma(\omega, t) = \sigma_0 + c\left[\int_0^\infty k^2|Y(k;\omega,t)|^2 dk\right]^{1/2} \tag{1}$$

with

$$d|Y(k;\omega,t)| = -\alpha k|Y(k;\omega,t)d\omega + \beta k^2\left[|\bar{Y}(k)| - |Y(k,\omega,t)|\right]dt \tag{2}$$

where ω is fault slip. $|Y|$ and $|\bar{Y}|$ are the Fourier component of fault surface topography and its maximum restorable value, respectively. The abrasion rate α and adhesion rate β are the position-dependent parameters, prescribing physical properties of fault surface.

We modeled the fault with two asperities ($30km \times 20km$ and $50km \times 20km$), separated by the creep zone ($10km$ in length). This situation is achieved by the smoothly distributed β, the adhesion rate, which controls the healing process of the fault. As demonstrated by Matsu'ura and Sato (1997)[7], the stress accumulation rate depends on the size of asperity. In the small asperity stress accumulate more rapidly. Thus the stress condition becomes different though the earthquake cycle.

We used the boundary integral equation method (Fukuyama and Madariaga, 1998[4]). We modified the Fukuyama and Madariaga's method in order to apply any shapes of constitutive relation between slip and stress at each point on the fault. We used the constitutive relation computed by the quasi-static simulation (Hashimoto and Matsu'ura, 2000[5][6]), which is

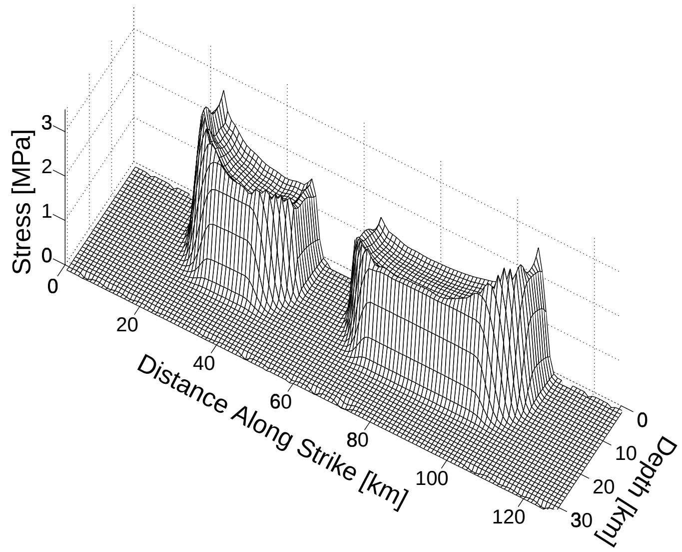

Figure 2: Initial stress distribution obtained by the quasi-static simulation.

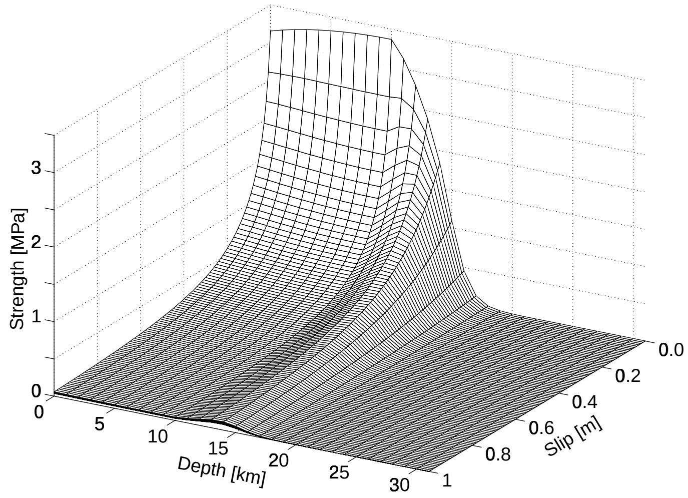

Figure 3: Constitutive relations obtained in the quasi-static simulation and used for the dynamic simulation. Although we used different constitutive relation for each point on the fault, we only plot along the depth axis at the middle of the small asperity (34km from the edge of the fault).

based on the slip and time dependent law (Aochi and Matsu'ura, 1999[1]). We used the constitutive relation just before the dynamic fracture as well as the stress distribution on the fault. Initial stress distribution for the dynamic fracture is shown in Figure 2. The slip weakening friction used in this dynamic analysis is shown in Figure 3. Since we used the vertical strike slip fault, we included free surface effect by introducing the mirror image approximation (Quin, 1990[8]).

Result of Computation

In Figure 4 we show a series of snapshots of stress and slip distributions at a constant time interval. "t=0s" corresponds to the time when the dynamic rupture started. In this computation, the rupture initiated at the left bottom edge of the small asperity and it propagated rightward. Whole small asperity was broken first in about 50 seconds and then the rupture transfered to the big asperity. The big asperity was broken in about 80 seconds. The slip inside the asperity grew gradually for about 50 seconds. The whole rupture duration time is about 200 seconds.

In this computation, instability occurred at the initiation point of the rupture and it propagated outside dynamically. Since the stress field is computed quasi-statically, the artificial trigger for the rupture initiation was not necessary. The rupture finally broke both asperities. This is because the initial stress level is almost critical in both asperities and constitutive relation is very similar between them. If we use the stress snapshot in different earthquake cycle where the stress accumulation is different between the asperities, different dynamic rupture would be reproduced.

Conclusion

We have successfully simulated the dynamic rupture propagation in the sequence of the quasi-static simulation of earthquake cycle at the transcurrent plate boundary. The resultant stress and fault slip distribution will be provided to the quasai-static simulation for the next earthquake cycile. Since we employed the slip and time dependent constitutive law and initial stress distribution consistent with the quasi-static simulation, the rupture started and propagated in proper way.

Acknowledgments

This work was done under the project entitled “Crustal Activity Modelling Program” (CAMP), which is supported by the Science and Technology Agency.

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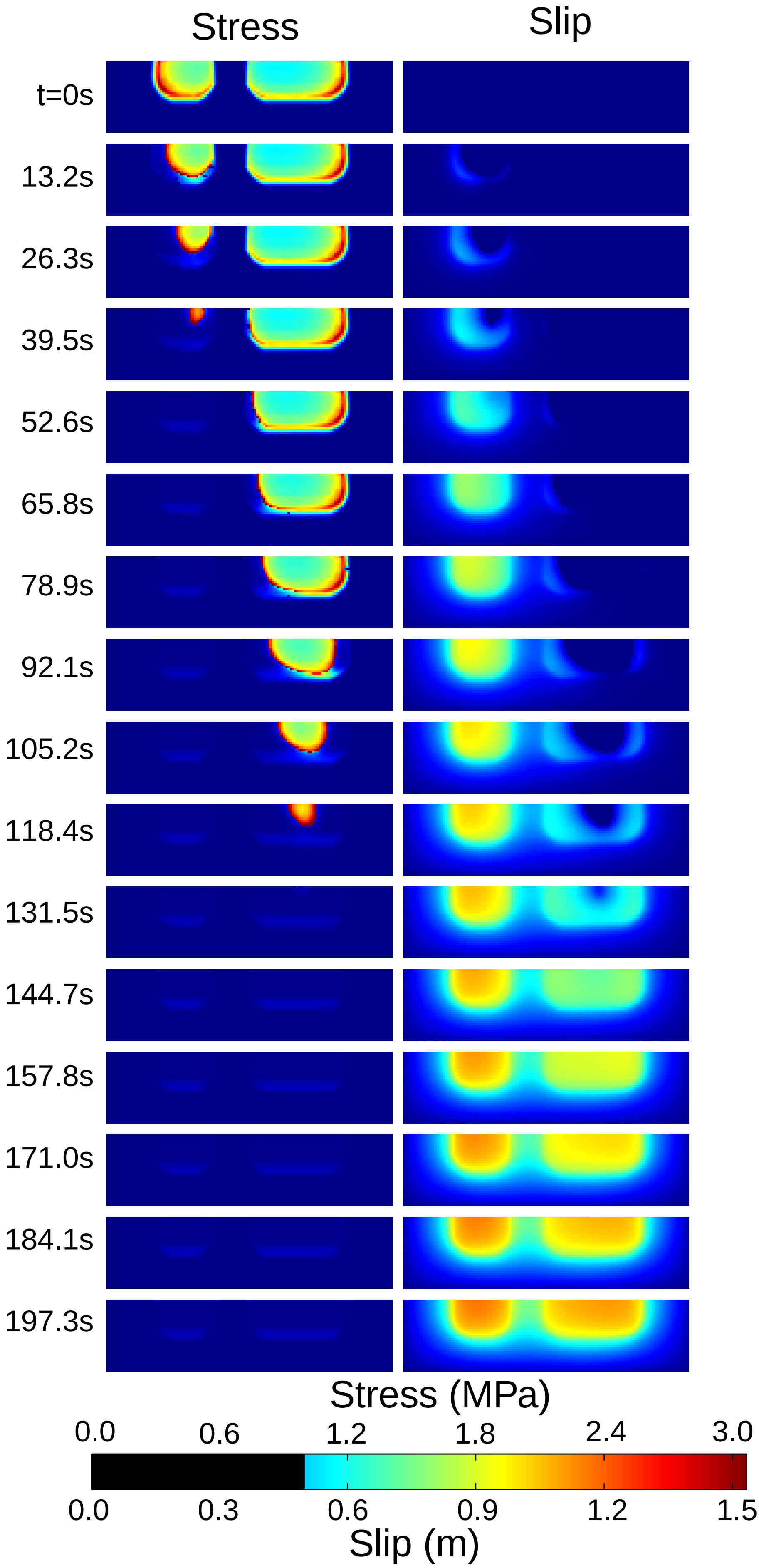

Figure 4: Example of the dynamic rupture propagation. Left and right raws show the snapshots of stress and slip distribution during the dynamic rupture. Scales are shown at the bottom using a color bar.