Rate- and Roughness-Dependent Fault Constitutive Law and Dynamic Earthquake Sequence Simulation

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1. Introduction

What physics governs the multi-scale source property of earthquakes, such as fracture energy scaling (e.g., Viesca & Garagash, 2015), is an interesting, long-lasting question. The fracture energy scaling indicates that energy dissipation during the dynamic event has a power law relationship with the coseismic displacement (e.g., Viesca & Garagash, 2015). Many studies adopted the rate- and state-dependent friction (RSF) law (Dieterich, 1978, 1979; Ruina, 1983) to simulate earthquake sequences. Although many aspects of the fault slip can be expressed by the RSF framework, such a multi-scale property is absent in the conventional RSFs. Therefore, in this study, we pursue a way to properly incorporate the multi-scale source properties of earthquakes into the RSF framework.

We utilize the slip- and time-dependent fault constitutive (STF) law (Matsu'ura et al., 1992; Aochi & Matsu'ura, 2002). They account for the evolution of fault surface roughness by abrasion (flattening) and adhesion (healing), whose characteristic slip and time, respectively, depend on the wavelength. The shear strength is expressed by the sum of contributions from the roughness of different wavelengths. Particularly, the roughness of a larger wavelength evolves more slowly but has a larger contribution than that of a smaller wavelength. This property potentially replicates the fracture energy scaling.

The introduction of the direct rate dependency can be regarded as the modernization of the friction law (Nakatani, 2001), which enables us to treat diverse fault behaviors in a single framework (e.g., dynamic earthquake sequence simulation) such as dynamic rupture, slow nucleation, and slow slips. Thus, we modify the STF law by adding the rate dependency and treat it as a form of RSF law, named rate- and roughness-dependent fault constitutive (RRF) law. The rate dependency and Fourier roughness (state) dependency can express the fault shear stress. We will discuss the property of RRF in the dynamic earthquake sequence simulation.

2. Formulation and Method

It is assumed that the shear strength is dictated by the topography of slip surface y in the slip direction z, and the existence of representative elementary length scale L_{f} in the direction of z (Fig 1). The Fourier transform of y for a set of wavenumbers k_{i}, $|Y(k_{\mathrm{i}})|$ work as state variables. They evolve by the abrasion and adhesion as follows:

$$\frac{\mathrm{d}|Y(k_{\mathrm{i}})|}{\mathrm{d}t} = -\alpha k_{\mathrm{i}} V |Y(k_{\mathrm{i}})| + \beta k_{\mathrm{i}}^2 (|\bar{Y}(k_{\mathrm{i}})| - |Y(k_{\mathrm{i}})|)$$

where α is the abrasion coefficient, β is adhesion coefficient, and $|\bar{Y}(k_{\mathrm{i}})|$ is the upper limit of $|Y(k_{\mathrm{i}})|$. The integration (summation) of Fourier roughness expresses the shear strength Φ:

$$\Phi = \tau_{\mathrm{c}} + C\left[\sum_{\mathrm{i}=1}^{\mathrm{n}} k_{\mathrm{i}}^2 |Y(k_{\mathrm{i}})|^2\right]^{1/2}$$

where τ_{c} and C are constant. The RRF can be written as follows:

$$\tau = A \log\left(\frac{V}{V_0}\right) + \Phi$$

where A is the coefficient for the direct effect, V is the slip rate, and V_0 is the reference slip rate.

This is coupled with elastodynamics, and the fault behavior is simulated with the spectral boundary integral equation method (Lapusta et al., 2000) and a flexible, adaptive time-step scheme (Romanet & Ozawa, 2022). We consider a 1-dimensional planar fault loaded by both ends at a constant rate V_{pl} (Fig 1).

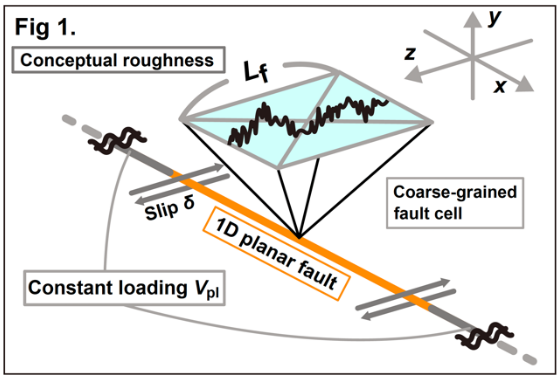

Fig 1. Schematic illustration of problem setting. At each fault cell, RRF is applied and conceptually coarse-grain the roughness in slip direction (black jugged curve).

We choose $L_{\mathrm{f}} = 10$ m, pick up 1500 Fourier modes (from the scale of 10 m to ~6 mm wavelength), and fix the following parameters within the seismogenic zone: $\tau_{\mathrm{c}} = 25$ MPa, $A = 0.5$ MPa, $C = 200$ MPa, $V_{\mathrm{pl}} = V_0 = 3 \times 10^{-9}$ m/s.

3. RRF reproduces fracture energy scaling

We change the parameter β/α, a ratio of adhesion to abrasion, and introduce representative 3 cases. Case I is the single, periodic dynamic rupture under $\beta/\alpha = 10^{-9}$, Case II is the sequence with quasi-static events and creep coalescence events under $\beta/\alpha = 10^{-10}$, and Case III is the slow slip sequence under $\beta/\alpha = 10^{-12}$.

Highlighting the result, in the sequence under $\beta/\alpha = 10^{-10}$, events of various sizes occur, and we find that the fracture energy of those events reproduces the scaling property (Fig 2). However, looking at the slip history, the RRF produces an unrealistically large afterslip in the coseismic slip area (Fig 3, left). Since it is rarely observed in nature, we currently attempt to regularize this property (Fig 3, right).

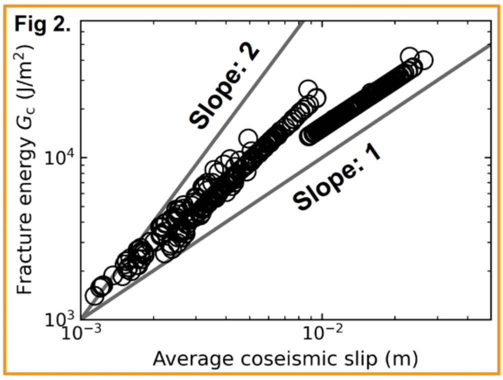

Fig 2. The fracture energy scaling under $\beta/\alpha = 10^{-10}$. A circle corresponds to a single event.

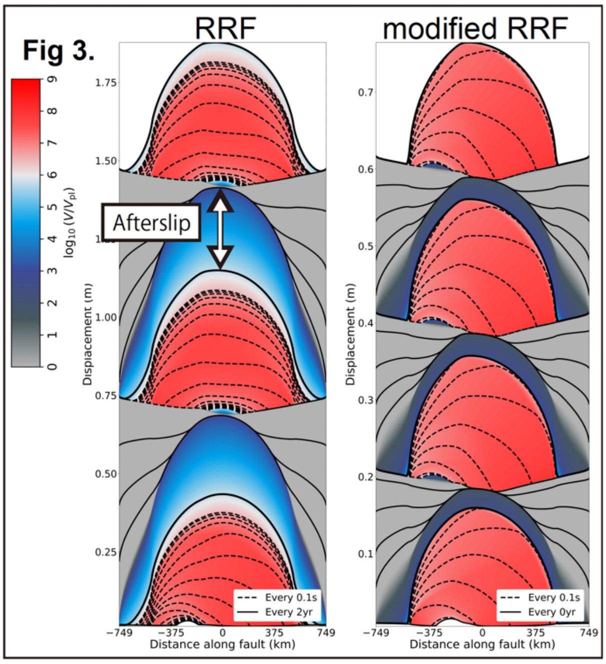

Fig 3. Displacement snapshot on the fault color-coded by the slip rate normalized by the loading rate V_{pl}.

The regularization is based on the result of the friction experiment that the direct effect tends to vanish as the slip rate increases (Takahashi et al., 2017). Thus, we introduce the cut-off slip rate V_{c} and regularize the rate-dependent term such that the direct effect saturates at the high slip rate:

$$\tau = A \log\left(\frac{V}{V + V_{\mathrm{c}}}\right) + \Phi$$

Investigation of whether the fracture energy scales or not with the modified RRF is in progress.