P17

Thermoelastic Instability on a Frictional Surface and Its Implication for Size Effect in Friction Experiments

○Hiroyuki NODA

1. Introduction

The laboratory friction experiment is one of the important approaches to understanding the mechanical properties of faults. However, there is a large difference in the length scale between laboratory samples and natural faults that host large earthquakes or slow earthquakes. Therefore, it is important to investigate the applicability and upscale of experimental results to natural faults. Tsutsumi and Shimamoto (1997) discovered that the rock friction coefficient drops remarkably at coseismic slip rate (0.1-1 m/s). This effect is called dynamic weakening of a fault, and considered to be caused by various mechanisms depending on the experimental condition activated by frictional heating (e.g., Rice, 2006). More recently, the scale effect of the high-velocity friction was experimentally investigated by Yamashita et al. (2015), who reported that larger samples showed dynamic weakening at lower slip rates. Those authors explained the result in terms of normal stress heterogeneity and associated concentration of frictional heating, which causes local activation of dynamic weakening.

Normal stress heterogeneity may be due to insufficient precision in the preparation of frictional surfaces. If this were the case, then the observed size effect might be suppressed by very careful surface preparation. In the field of tribology, growth of normal stress heterogeneity due to thermoelastic instability (TEI, e.g., Burton, 1980) at high slip rates has been studied. TEI yields a lower critical slip rate for heterogeneity of a longer wavelength and thus may lead to the sample-size effect as Yamashita et al. (2015) observed. In this study, an efficient numerical algorithm was proposed for numerical simulation of TEI in a quasistatic two-dimensional problem (Figure 1) based on a spectral boundary integral equation method for future implementation into simulations of earthquake sequences. Evolution of the normal stress heterogeneity of a single wavelength component was simulated, and discuss if TEI operates during published friction experiments.

2. Formulation

Fault planes are rough, anisotropic, and typically show lineations referred to as slickenlines. Such geometrical heterogeneity may cause 1-dimensional distribution of the normal stress σ_n parallel to the slip direction (Fig. 1a). This simplification leads to a 2-dimensional problem of thermoelasticity for a infinite medium with a straight faut which acts as a source of frictional heat. The change in the normal stress $\Delta\sigma_\mathrm{n}$ is expressed by a boundary integral,

$$\Delta\sigma_\mathrm{n}(x,t) = \int_{-\infty}^{t}\int_{-\infty}^{\infty} q(x',t')G(x-x',t-t')\,\mathrm{d}x'\mathrm{d}t'$$

where q is the frictional heat density and G is Green's function. Fourier transformation leads to

$$\Delta\tilde{\sigma}_\mathrm{n}(k,t) = \int_{-\infty}^{t} \tilde{q}(k,t')\tilde{G}(k,t-t')\,\mathrm{d}t'$$

where k is the angular wavenumber. $\tilde{G}$ is written as

$$\tilde{G}(k,t) = \frac{2\alpha|k|}{\gamma C}\,\mathrm{erfc}\big(|k|\sqrt{Dt}\big)$$

where α is the change in pressure by unit change in temperature under fixed displacement boundary condition, C the is specific heat capacity, D is the diffusivity of temperature, and γ is a function of Poisson's ratio. Assumption of constant friction coefficient f and slip rate V leads to

$$\tilde{\eta}(s) = 2v\int_0^s \left(1+\tilde{\eta}(s')\right)\mathrm{erfc}\left(\sqrt{s-s'}\right)\mathrm{d}s'$$

where $\tilde{\eta} = \Delta\tilde{\sigma}_\mathrm{n}(k,t)/\tilde{\sigma}_\mathrm{n}(k,0)$, $s = Dk^2t$, and $v = V/V_\mathrm{cr}$. V_cr is the critical slip rate $\gamma CD|k|/\alpha f$. Perturbation grows if $v > 1$ and decays if $v < 1$ (e.g., Burton, 1980).

The temporal convolution was approximated into ordinal differential equations of memory variables ϕ_i (e.g., Noda, 2022)

$$\frac{\mathrm{d}\phi_i}{\mathrm{d}s} = 2v\left(1+\tilde{\eta}(s)\right) - \frac{\phi_i}{s_i}$$

where

$$\tilde{\eta}(s) \approx \sum_{i=1}^{n} a_i\phi_i\,, \mathrm{erfc}\left(\sqrt{s}\right) \approx \sum_{i=1}^{n} a_i \mathrm{e}^{-s/s_i}\,.$$

They were integrated by second-order exponential time-differencing method (e.g., Noda and Lapusta, 2010). Compared with the standard SBIEM, the present method yields comparable level of numerical error for about one order of magnitude shorter computational time and without requirement of history storage. It is advantageous in future implementation into earthquake sequence simulations.

3. TEI during friction experiments and fault slip

Numerical results (Fig. 1b and c) reproduced the previous report on the critical slip rate in TEI (e.g., Burtonm 1980). The normal stress heterogeneity grows indefinitely at $v \geq 1$, and approaches to the steady state at $V < 1$.

The possibility of TEI during friction experiment is investigated based on physical properties of gabbro. For a sample of 1 cm in width, $V_\mathrm{cr} = 1.32$ cm/s and the chatacteristic time $t_\mathrm{c} = 2.91$ s, which correspoinds to $s = 1$. For a sample of 10 cm in width, $V_\mathrm{cr} = 1.32$ mm/s and $t_\mathrm{c} = 291$ s. These values drop in a commonly adopted range of experimental conditions. Therefore, evaluation of TEI during friction experiments by measurement of temperature distribution deserves future study.

At coseismic slip rate, TEI occurs in a very small length scale. At $V = 1$ m/s, the critical wavelength becomes 0.132 mm. Numerical resolution of such a small length scale is difficult in simulations of large earthquakes. Future studies on coarse graining of the high-velocity friction are important.

References

Burton, R. A. (1980). *Wear*

Noda, H. & Lapusta, N. (2010). JGR

Noda, H. (2022). *EPS*.

Rice, J. R. (2006). *JGR*.

Tsutsumi, A. & Shimamoto, T. (2997). *GRL*.

Yamashita, F. et al. (2015). *Nature*

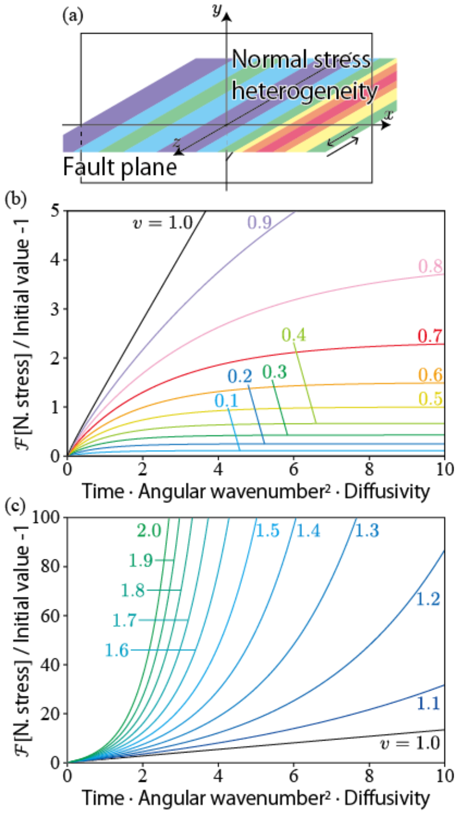

Fig. 1 (a) Schematic diagram of the two-dimensional problem for a planar fault with heterogeneous normal stress. (b and c) Evolution of normal stress heterogeneity in the (b) low and (c) high slip-rate regimes. v is the nondimensional slip rate V/V_cr.