Poroelastic Bimaterial Effects in Rupture Dynamics

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1. Abstract

A mismatch of elastic properties across a fault induces normal stress changes during spatially nonuniform slip. Recently, Rudnicki and Rice (2006) showed that similar effects follow from a mismatch of poroelastic properties (e.g., permeability) within fluid-saturated damage fringes along the fault walls; those induce changes in pore pressure on the slip plane and hence changes in effective normal stress during slip. The sign of both changes can be either positive or negative, and they need not agree. Both signs reverse when the rupture propagates in the opposite direction, introducing asymmetry into the rupture process.

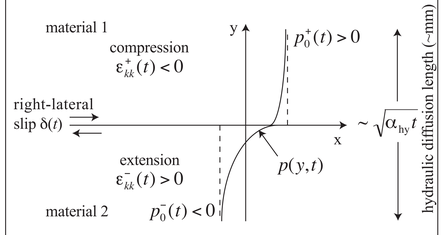
We model a poroelastic fault zone cut by a planar fault separating regions of potentially different poroelastic properties. Slip compresses one side of the fault while dilating the opposite side. The resulting undrained pore pressure change is of opposite sign across the fault, and pore fluid diffuses to ensure continuity of pore pressure and fluid flux across the fault. Pore pressure on the fault decreases if the compressive side is less permeable (all other quantities being equal) and vice-versa. The poroelastic properties are measured over the hydraulic diffusion length, generally of order a few millimeters in well-sheared fault core cataclasite for a slip duration of a few seconds. (Poroelastic effects are essentially negligible on that time scale at greater distances from the fault because of vastly smaller pore pressure gradients; the material responds there like a classical elastic solid with moduli based on undrained poroelastic response.)

Steady sliding of two half-spaces (neglecting shear heating) with identical elastic properties but a mismatch in poroelastic properties is unstable to perturbations for all non-zero values of the friction coefficient and Skempton's coefficient. The growth rate is proportional to the wavenumber of the perturbation, rendering this problem ill-posed in a manner similar to that for elastic mismatch. When both elastic and poroelastic properties are discontinuous across the fault, sliding is unstable for arbitrarily small friction coefficients if the elastic mismatch permits the existence of a generalized Rayleigh wave. When the poroelastic effect opposes the elastic bimaterial effect, there exists a critical parameter set at which the effects precisely balance and sliding is neutrally stable. The propagation direction of the unstable mode reverses across this critical state. For a large elastic mismatch, the generalized Rayleigh wave goes out of existence and sliding is stabilized for friction coefficients less than some critical value; this value is altered by the poroelastic response.

This stability analysis is augmented by calculations of spontaneous ruptures on slip-weakening faults across which elastic and poroelastic properties may be discontinuous. Prakash-Clifton regularization permits convergent solutions in the otherwise ill-posed regime. The numerical method is validated by comparison to analytical solutions for the rupture of a line asperity between dissimilar elastic solids in frictionless contact (Harris and Day, 1997) and for a self-similar crack between identical elastic solids but with a mismatch in poroelastic properties.

2. Poroelastic Fault Zone Model

(Rudnicki and Rice, 2006)



Planar fault surrounded by fluid-infiltrated damage fringes, which may have *different* elastic/poroelastic properties compared to material further away

1. Slip compresses one side and dilates other
2. Undrained (instantaneous) pore pressure response given by

$$p_0(t) = -BK_u\varepsilon_{kk}(t)$$

B = Skempton's coefficient
K_u = undrained bulk modulus
ε_{kk} = dilation

3. Fluid diffuses (with hydraulic diffusivity α_{hy}) to satisfy continuity of pore pressure $p(y,t)$ and fluid flux $q(y,t)$

When one side is far more permeable than other, then pore pressure on fault equals undrained value on highly permeable side. This follows from continuity conditions and Darcy's law:

$$q(y,t) = -\frac{\rho_f k}{\eta_f}\frac{\partial p}{dy}$$

k = permeability
ρ_f = fluid density
η_f = fluid viscosity

3. Induced Pore Pressure on Fault Plane

When crossing into damage fringes, σ_{yy} and ε_{xx} are continuous, but ε_{yy} and σ_{xx} are discontinuous.

$$p = -q_0\sigma_{yy} - q_1\mu_1\varepsilon^{+}_{xx} - q_2\mu_2\varepsilon^{-}_{xx}$$

$$q_0 = \frac{1}{2}\sum_{i=1}^{2}\left[\frac{Z_i}{Z_1+Z_2}\right]\left[B_i\frac{2(1+\nu_{ui})}{3(1-\nu_{ui})}\right]$$

$$q_i \underset{(i=1,2)}{=} \left[\frac{Z_i}{Z_1+Z_2}\right]\left[B_i\frac{2(1+\nu_{ui})}{3(1-\nu_{ui})}\right]\left[\frac{\mu_{ui}}{\mu_i}\right]$$

permeability contrast factor

poroelastic coupling factor

ratio of shear modulus inside damage fringe to that outside

$$Z_i = \sqrt{k_i\beta_i}$$

k = permeability
β = storage factor

Model Parameters

	more damaged	less damaged
k_i	k_d	$k_d/10$
β_i	β_d	$\beta_d/2$
B_i	0.6	0.4
ν_{ui}	0.3	0.3
μ_{ui}/μ_u	0.25	0.5
q_i	0.15	0.045

$q_0 = 0.35$

4. Stability Analysis

Is steady sliding at constant f stable to perturbations?

Add Fourier mode perturbation e^{ikx+st} to steadily sliding half-spaces obeying

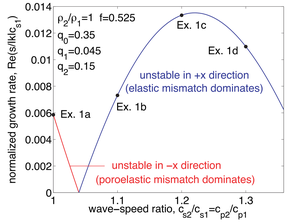
$$\tau = f(\sigma - p)$$

with constant f. Unstable if Re(s)>0, propagating if Im(s) is nonzero.

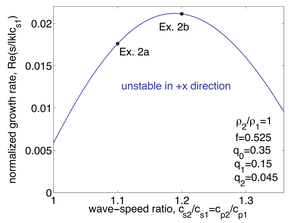
Stability properties are similar to those found by Ranjith and Rice (2001) for sliding between dissimilar elastic solids, but with added richness since poroelastic and elastic bimaterial effects can either *oppose* or *enhance* each other.

Case I. Small elastic mismatch permits existence of generalized Rayleigh wave in frictionless sliding. Combination of elastic bimaterial response and poroelastic response causes instability for arbitrarily small f. Always unstable (and ill-posed) except when effects precisely balance each other.

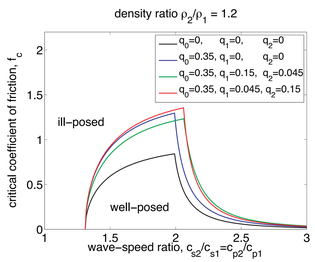
Opposing Effects
poroelastic effect ⟵
elastic mismatch ⟶

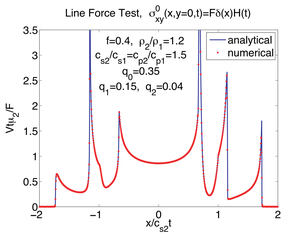


Enhancing Effects
poroelastic effect ⟶
elastic mismatch ⟶



Case II. Large elastic mismatch forbids existence of generalized Rayleigh wave in frictionless sliding. Combination of elastic bimaterial response and poroelastic response causes instability, but only when f exceeds a critical value (f_c). Stable (well-posed) region provides testing ground for numerical methods.

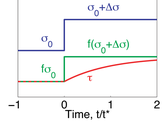




Extension of Harris and Day (1997) solution to frictional sliding between solids with mismatch in elastic and poroelastic properties

5. Regularization to Remedy Ill-Posedness

Regularization provided by introducing a time scale t^* over which strength τ evolves toward $f(\sigma\text{-}p)$. Necessary for numerical solutions to be convergent.



Must satisfy:
1. $\Delta t << t^*$ to ensure numerical resolution
2. $t^* <<$ (duration of slip-weakening process) to avoid artifically delaying rupture

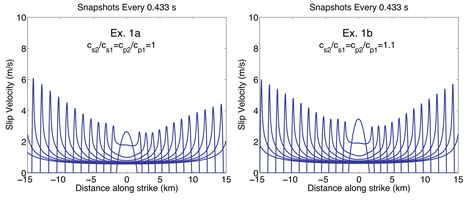
$$\frac{d\tau}{dt} = -\frac{1}{t^*}\left[\tau - f(\delta)(\sigma - p)\right]$$

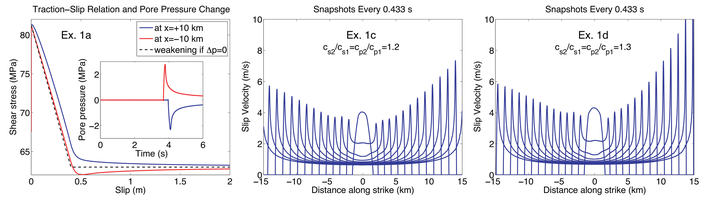
6. Spontaneous Ruptures in 2D

Modeled with spectral BIE code for elastic bimaterial problems. Fault-parallel strains calculated by evaluating displacement gradients using spectral methods. Linear slip-weakening law, $\tau=f(\delta)(\sigma\text{-}p)$, regularized with t^*=0.01 s. Parameters similar to SCEC rupture dynamics validation tests, but with lower initial stress (to prevent supershear): ρ=2670 kg/m^3, c_{s2}=3.464 km/s, c_{p2}=6 km/s, τ_0=67.56 MPa, σ_0=126 MPa, f_s=0.677, f_d=0.525, D_c=0.4 m. Nucleation by overstressing asperity 3 km wide to τ_0=81.6 MPa. Grid size h=12.5 m

Ex. 1a-d *Opposing Effects*
⟵ poroelastic effect
elastic mismatch ⟶

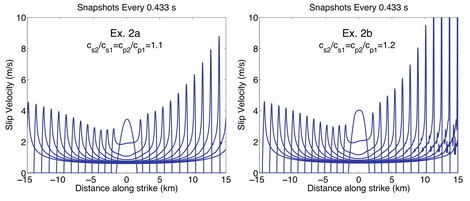
Elastic mismatch increases from a to d, eventually overwhelming poroelastic effect





Ex. 2a-b *Enhancing Effects*
poroelastic effect ⟶
elastic mismatch ⟶

Strong asymmetry in rupture process for all elastic mismatches



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