Modelling of fluid injection into a frictional weakening dilatant fault

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Introduction

Fluid injection at a pressure below the local minimum principal total stress in a fault may (re)activate shear crack propagation (hydroshearing). Because of the presence of asperities along the fault's surfaces, the fault hydraulic width increase with the slip (up to a constant value).

The question we want to address in this contribution is the following: does the increment of hydraulic width (dilatancy) affect the shear crack propagation along the fault? does it play a role in the shear crack propagation of unstable faults?

Garagash & Germanovich [1] showed that a fault subjected to locally elevated pore pressure associated with fluid injection hosts different limiting regimes depending on how far the initial stress state is from its strength level. Notably when a fault is stressed almost to its static strength level (*critically loaded fault*), a large slip zone is expected. Hence at the nucleation time, the pressurized region is within the slipping patch. On the other hand, for a *marginally pressurized fault* (i.e when the pore pressure is just enough to activate the slip), the slipping patch is much slower than the diffusive growth of the pressurized zone.

In addition to this, they showed that the regime of propagation of such pressurized faults can be *ultimately stable* or *unstable* depending on whether the initial shear stress state is greater or lower than the fault residual strength. In the former case the shear crack propagates with a moderate velocity (quasi-static) as it is induced by fluid pressure diffusion (but it might turns into a dynamic instability followed by an arrest). In the latter case, the shear crack initially propagates quasi-statically; then, as slip accumulate along the fault, the quasi-static crack growth become unstable and the shear crack runs away.

The effect of dilatancy leads to a local reduction of pore-pressure at the shear crack tip depending on the ability (viscosity-related) of the fluid to flow in the newly created void space, leading to a stabilising effect [2].

Numerical scheme description

The elasticity equation (1) is solved numerically using Displacement Discontinuity Method (with piecewise linear shear displacement discontinuities), whereas the fluid flow is discretised using Finite Volume Method (3).

The algorithm solves the fully coupled problem with an implicit scheme: in one increment of time, it calculates the current increment of pressure and increment of slip (by making use of the current total slip and pressure distribution) and at the same it enforce the M-C criterion (2). As a result, the slippage length is calculated.

The non linear system of equations (the dilatancy depends on the current slip) is solved using fixed point iterations combined with under relaxation.

Conclusion

- Figures 2 and 3 show that our code matches perfectly the semi-analytical solution of Garagash & Germanovich (2012) for the case of non-dilatant fault.
- Depending on the ratio between the background shear stress and the ambient frictional strength, a fault can host a dynamic instability followed by an arrest (ultimately stable fault, figure 2 - left) or a dynamic instability without any arrest (unstable fault, figure 2 - right).
- The dilatant hardening directly affects the regime of propagation; its effect may suppress the dynamic instability for both ultimately stable faults and unstable faults. This is because of the pressure drops localised at the crack tip during high slip rate (figure 3 - left), which leads to an increment of effective stresses and consequently a stabilising effect.
- From figure 3 (right), we can observe (as expected) that the pressure drop for a marginally pressurized fault is within the pressurized region as the slipping patch is much slower than the diffusive growth of the pressurized zone.

References

[1] D. I. Garagash, and L. N. Germanovich Nucleation and arrest of dynamic slip on a pressurized fault. *J. Geophys. Res.*, 117, 2012.

[2] David A. Lockner, and James D. Byerlee Dilatancy in hydraulically isolated faults and the suppression of instability. *Geophysical Research Letters*, 21, 22, 2353-2356, 1994.

Quasi-static shear crack propagation under fluid injection

Let us consider an impermeable linear elastic medium with a long fault under a uniform background stress field characterised by the normal σ_n and shear τ^b components (Figure 1 - left). In addition to this, let us suppose the presence of a shear crack of a finite length $2a$ acting on the fault.

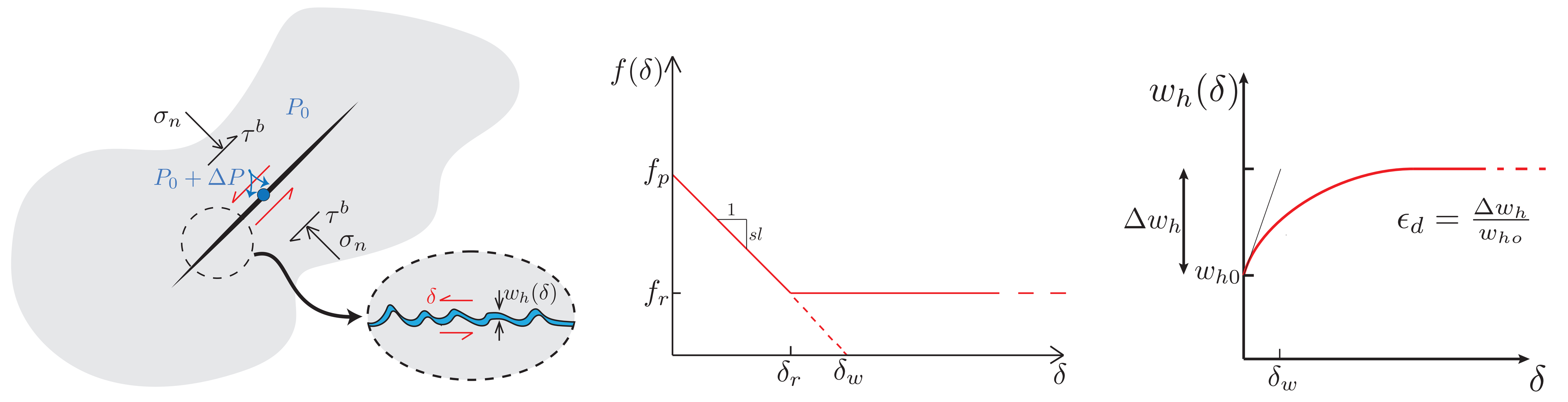

Figure 1: Model of shear weakening dilatant fault and loading conditions (left); Friction weakening law (center); Dilatant hardening law (right).

By applying the distributed shear dislocation theory, under a *Quasi-Static approximation* [?], the shear stress depends on the slip by means of the following singular integral equation of the first kind:

$$\tau(x,t) = \tau^b - \frac{G}{2\pi\cdot(1-\nu)}\int_{a_-(t)}^{a_+(t)} \frac{\partial\delta(s,t)}{\partial s}\frac{ds}{x-s}, \qquad |x|<a \tag{1}$$

where $\tau^b(x,t)$ is the background shear stress, G is the shear modulus, ν is the Poisson's ratio, $\frac{\partial\delta(s,t)}{\partial s}$ is the shear dislocation density, $\frac{1}{x-s}$ is the *simple Cauchy kernel*.

Within the fault region, we assume the shear weakening Mohr-Coulomb failure criterion. The shear stress on the fault must be less (or equal) to the fault shear strength:

$$\tau(x,t) \le f(\delta)(\sigma_n - p_0 - p(x,t)), \tag{2}$$

where p_0 is the ambient pore-pressure distribution in the fault, $(\sigma_n - p_0 - p(x,t))$, also denoted as σ', is the effective stress normal to the fault and the friction coefficient f is assumed to weaken linearly with slip (Figure 1 - centre).

Under the lubrication approximation and under the assumption of slightly compressible liquid of compressibility c_f, the width averaged mass conservation in the fault reduces to the following continuity equation

$$w_h c_f \frac{\partial p}{\partial t} + \frac{\partial w_h}{\partial t} - \frac{\partial}{\partial x}\left(\frac{w_h k_f}{12\mu}\frac{\partial p}{\partial x}\right) = 0, \tag{3}$$

where k_f is the fault permeability, μ is the fluid viscosity and w_h is the hydraulic aperture, which we assume it increases exponentially with the slip (dilatant hardening - Figure 1 - right). By doing a dimensional analysis, we can show that the problem is governed by the following dimensionless parameters:

$$\frac{\tau^b}{\tau_p}, \frac{\Delta p}{\sigma'_o}, \frac{f_r}{f_p}, \frac{\sqrt{\alpha t}}{a_w}, \frac{\epsilon_d}{c_f\sigma'_o}, \tag{4}$$

where $\alpha = \frac{k_f}{c_f\cdot 12\mu}$ is the hydraulic diffusivity, $a_w = \frac{\mu^*}{\tau_p}\delta_w$ is the patch length scale, $\epsilon_d = \frac{\Delta w_h}{w_{ho}}$ is the increment of dilatancy with respect to its initial value and $\sigma'_o = \sigma_n - p_o$ is the ambient effective stress.

Results

Solutions of the governing equations for an ultimately stable & unstable fault (in terms of normalized crack half-length a/a_w and normalized peak slip δ/δ_w) as a function of normalized time $\sqrt{\alpha t}/a_w$, understress $(\tau^b)/\tau_p$, overpressure $\Delta p/\sigma'_0$, $f_r/f_p = 0.6$ and dimensionless dilatancy parameter $\frac{\epsilon_d}{c_f\sigma'_o}$ are hereunder reported.

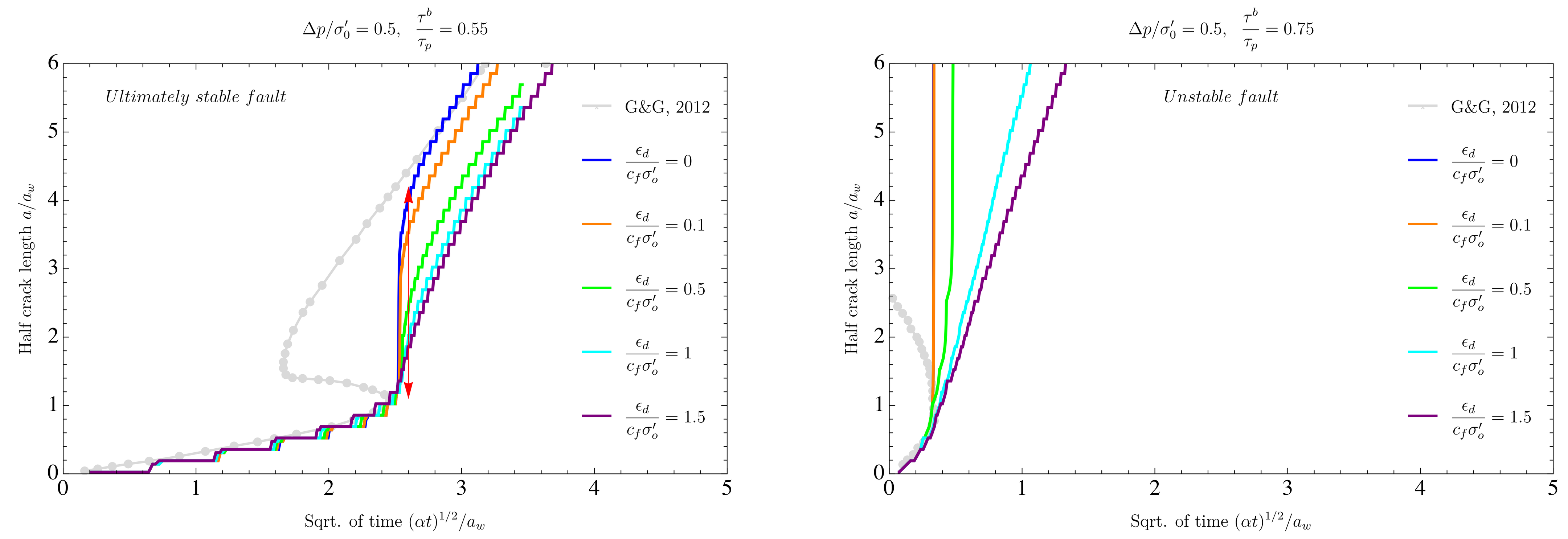

Figure 2: QS development of the normalised crack half-length for an ultimately stable fault ($\tau^b/\tau_p = 0.55$ - left) and for an unstable fault ($\tau^b/\tau_p = 0.75$ - right), for various values of dimensionless dilatancy coefficient $\frac{\epsilon_d}{c_f\sigma'_o}$ and a value of constant overpressure. The marked lines correspond to the G&G's results for quasi-static crack propagation without dilatant hardening [1].

The corresponding evolution of pore pressure profile for an ultimately stable fault characterised by $\tau^b/\tau_p = 0.55$ is

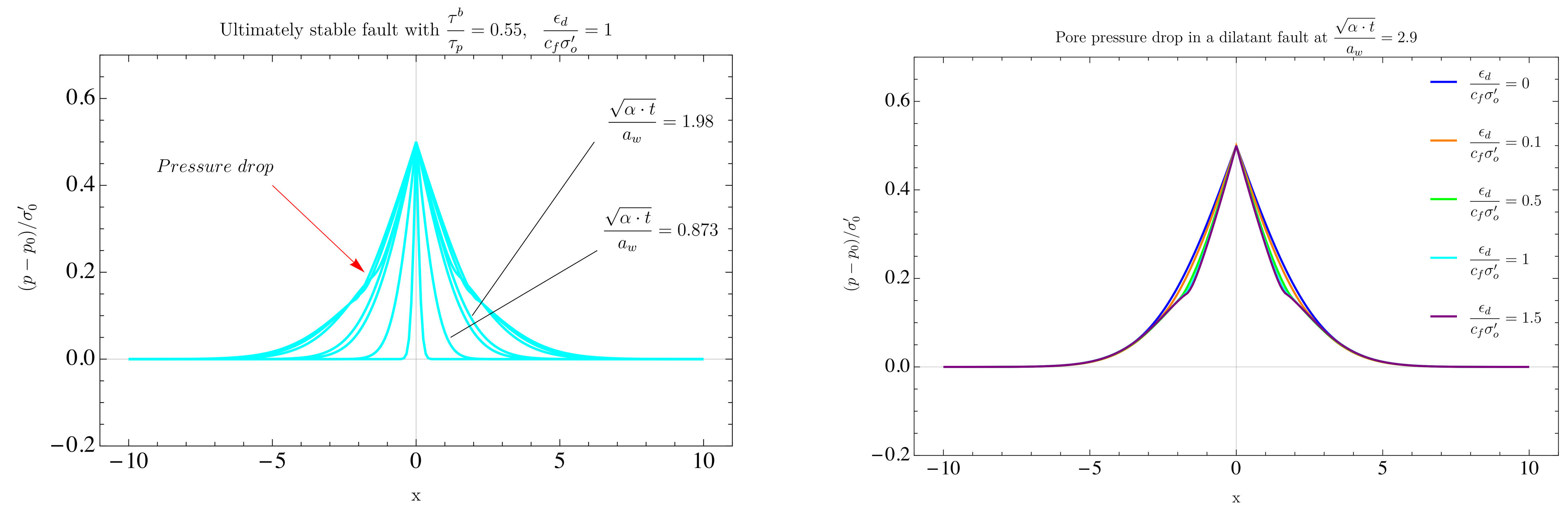

Figure 3: Pore pressure evolution for an ultimately stable fault characterised by $\tau^b/\tau_p = 0.55$ and $\epsilon_d = \frac{\epsilon_d}{c_f\sigma'_o} = 1$ (left). Snapshot of pore pressure profile at $\frac{\sqrt{\alpha t}}{a_w} = 2.9$ for an ultimately stable fault characterised different values of dimensionless dilatancy $\frac{\epsilon_d}{c_f\sigma'_o}$ (right).