Effect of dilatancy on a frictional weakening fault subjected to fluid injection

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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, fault hydraulic width increase with slip. Scaled experiments in fact show that dilatancy (inelastic increment of hydraulic width) varies non linearly with the slip up to a constant value (for large values of shear displacements) [3]. Its effect on pore pressure diffusion along the fault is a local drop at the crack tip. Depending on the ability of the fluid to flow in the newly created void space, the local effective stresses increase and this leads to a stabilising effect [2].

The questions we want to address in this contribution are the following: does the increment of hydraulic width (dilatancy) always kill the dynamic instability associated with a frictional weakening fault subjected to fluid injection? does the change of fault permeability associated with dilatant hardening affect the shear crack propagation?

Garagash & Germanovich [1] showed that the regime of propagation of 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. Notably, the local pore pressure drop and the consequent local increment of effective stress depends on the hydraulic diffusivity of the fault: we expect higher pressure drop for fault characterised by constant permeability (no change with fault dilatancy) than for fault whose permeability increase with dilatant hardening. So it is clear that there is an interplay between pressure drop associated with dilatant hardening and fault permeability change. In this contribution we want to investigate such an interplay for both ultimately stable and unstable faults.

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

- First of all, 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).
- For an ultimately stable fault whose permeability does not change with hydraulic width, the dilatant hardening either delay the onset of the dynamic instability as well as decrease its size or kill the dynamic event. At high slip rate, the shear crack velocity change with dilatancy parameter: it decrease for large value of dilatancy, up to a constant value.
- For unstable faults, we observe almost the same behaviour, except the fact that the shear crack velocity decrease monotonically with the dilatancy.
- As far as an ultimately stable fault whose permeability change with dilatant hardening is concerned, we observe that dilatant hardening may suppress the instability; however the higher is the dilatancy the higher is the shear crack velocity. This is because the pressure drop associated with increment of hydraulic width at high slip rate is lower due to the increment of permeability. The pore pressure is recovered faster so the shear crack velocity increase.

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.

[3] N. Barton, S. Bandis, and K. Bakhtar Strength, Deformation and Conductivity Coupling of Rock Joints. *Int. J. Rock Min. Sci. and Geomech.*, 22, 3, 121-140, 1985.

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.

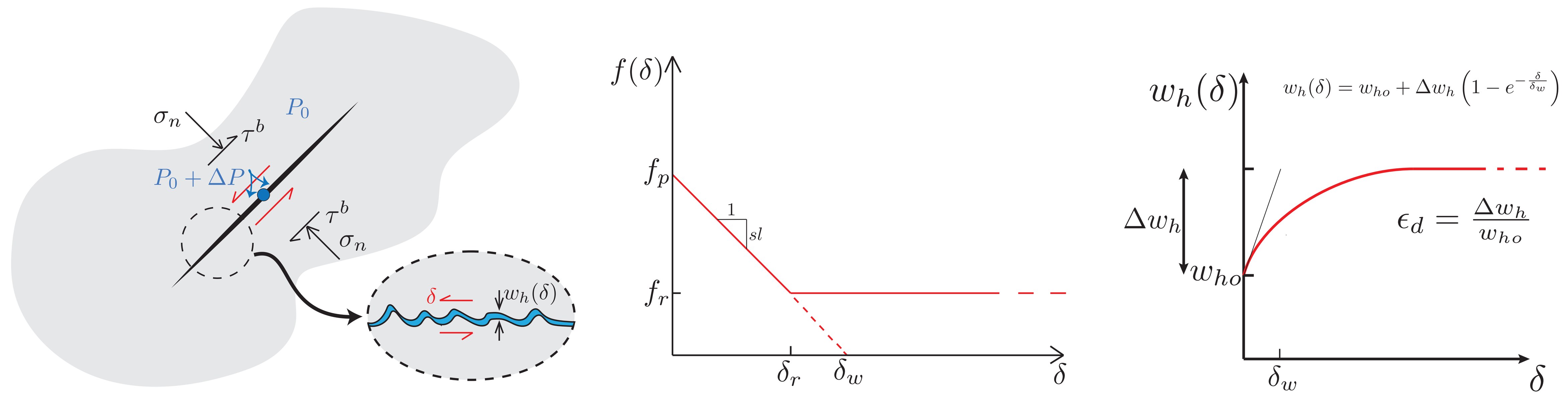

Figure 1: Model of shear weakening dilatant fault and loading conditions (left); Friction weakening law (center); Dilatant hardening law (right).

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, $a_w=\frac{G}{\tau_p\cdot(1-\nu)}\delta_w$ 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) 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 represents the results of a fault whose permeability does not change with slip (it is kept constant - $k_f=w_{ho}^2$).

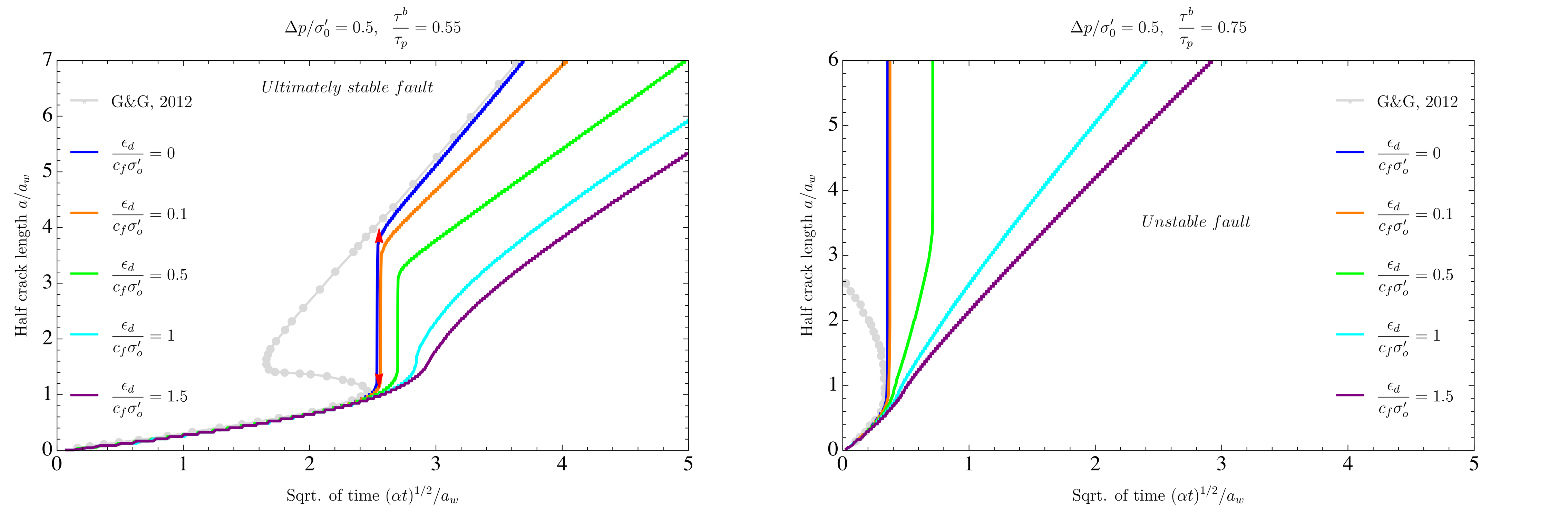

Figure 2: QS development of the normalised crack half-length for an ultimately stable fault ($\tau^b/\tau_p=0.55$ - left) and for an unstable fault ($\tau^b/\tau_p=0.75$ - right) whose permeability does not change with dilatancy, for various values of dimensionless dilatancy coefficient $\frac{\epsilon_d}{c_f\sigma_o'}$ 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 results for a fault whose permeability change with dilatancy ($k_f=w_h(\delta)^2$) are:

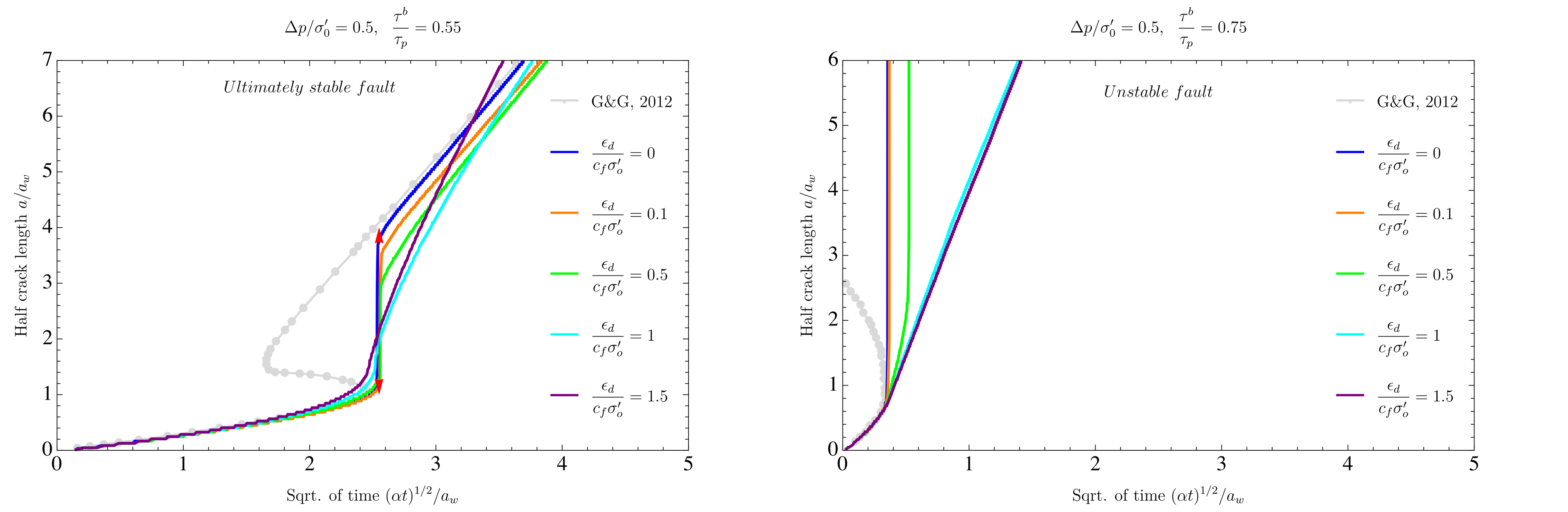

Figure 3: QS development of the normalised crack half-length for an ultimately stable fault ($\tau^b/\tau_p=0.55$ - left) and for an unstable fault ($\tau^b/\tau_p=0.75$ - right) whose permeability change with dilatancy ($k_f=w_h^2$), for various values of dimensionless dilatancy coefficient $\frac{\epsilon_d}{c_f\sigma_o'}$ 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].