EGU General Assembly 2024

Supplementary Material:

Injection Rate effects on failure of a saturated gouge- filled Fault: Dilation vs. Diffusion

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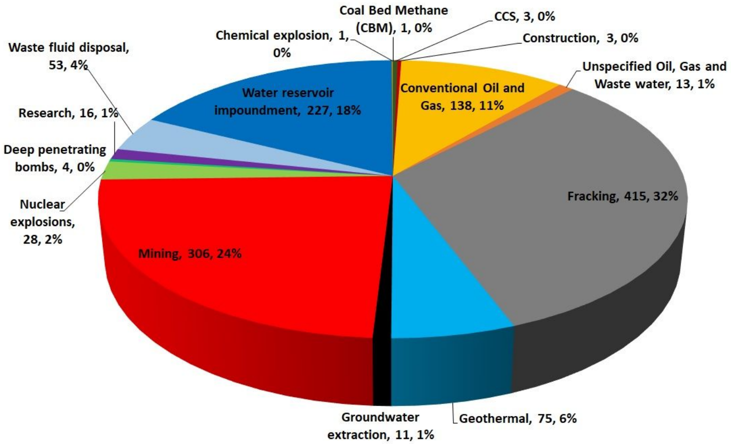
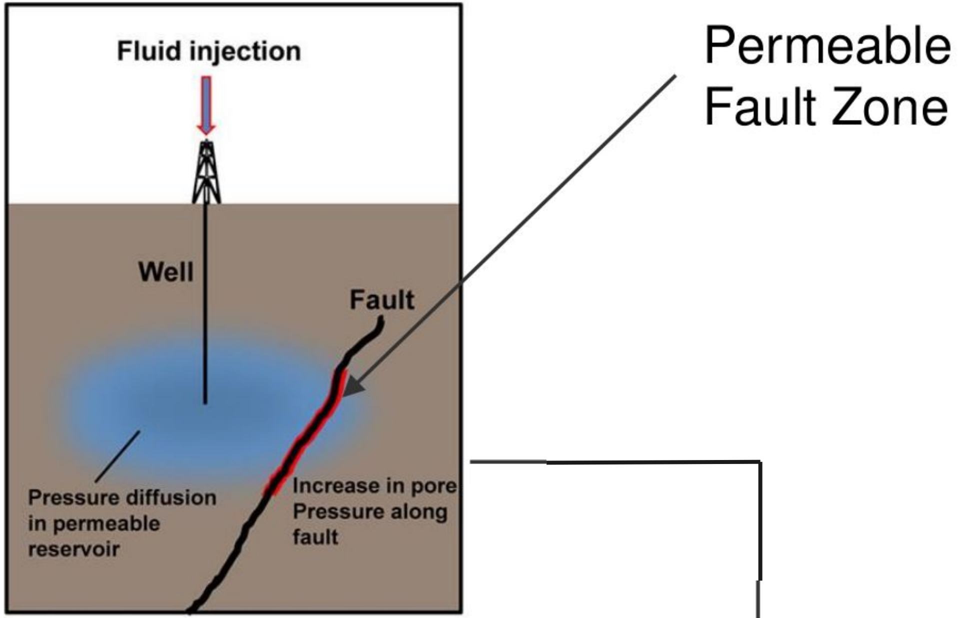
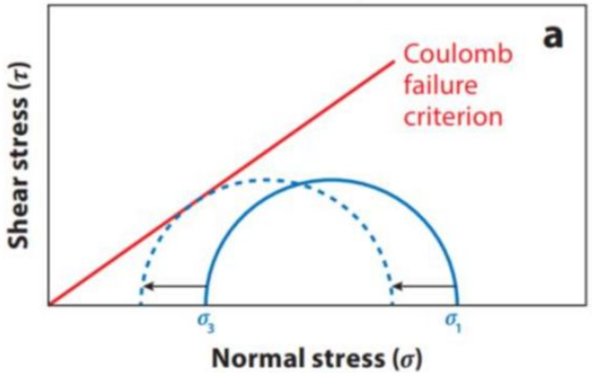
Background

- **Injection of fluids** into the subsurface has been linked to fault instability, causing a)**induced seismicity** and b)**aseismic creep.**



Data Source: www.inducedearthquakes.org

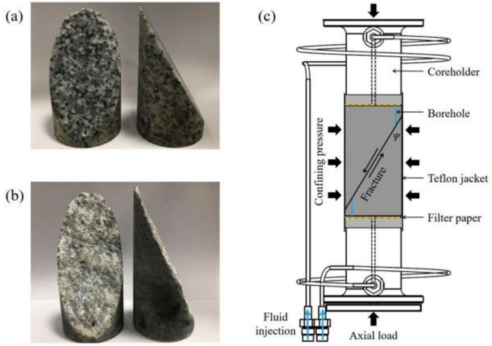




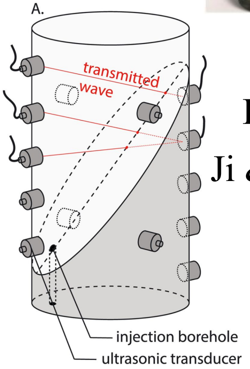
(Keranen and Weingarten, 2018)

Experimental Observations: Injection Rate vs. Failure Pressure

Recent experimental studies (Passelegue et al.,2018; Ji & Wu, 2020; Ji et al., 2021) show that slower injections lead to failure at lower pressures than fast injection rates.

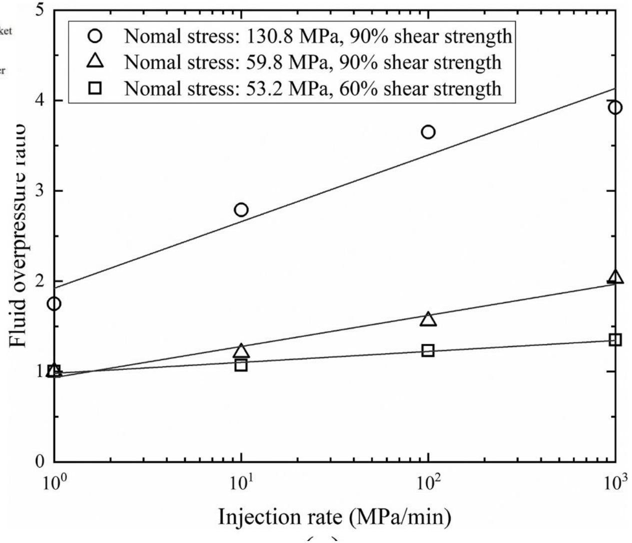


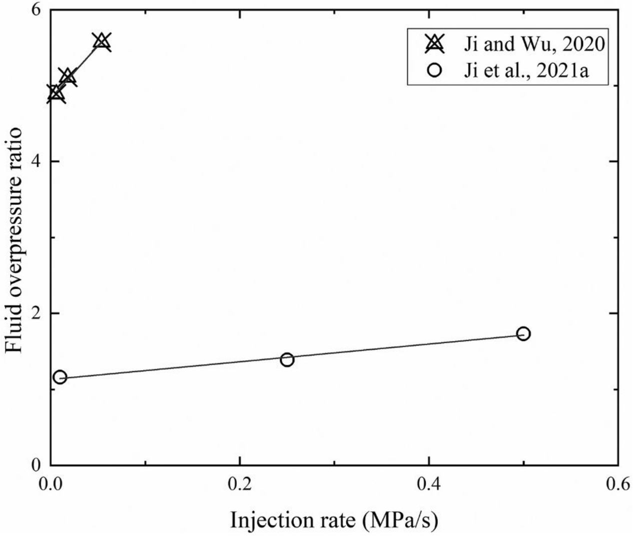
$$\text{Fluid Overpressure Ratio} = \frac{\text{Injection Pressure at Fault Failure}}{\text{Predicted Fluid Pressure with the Mohr-Coloumb failure creterion}}$$



Passelegue et al., 2018

Ji & Wu, 2020; Ji et al., 2021





Formulation for the physics of pore fluid

Grains mass conservation :

$$\frac{\partial[(1-\phi)\rho_s]}{\partial t}+\nabla\cdot[(1-\phi)\rho_s u_s]=0$$

Fluid mass conservation :

$$\frac{\partial[\phi\rho_f]}{\partial t}+\nabla\cdot[\phi\rho_f u_f]=0$$

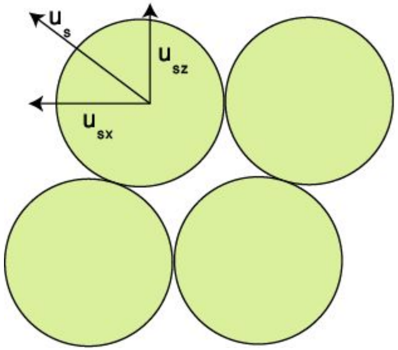
Darcy :

$$u_f-u_s=-\frac{k}{\mu\phi}\nabla p$$

Fluid state :

$$\rho_f=\rho_0(1+\beta p)$$

Fluid compressibility



$$\nabla\cdot u_s=\frac{\partial\Phi/\partial t}{\Phi(1-\Phi)}$$

Under the assumption of nearly incompressible grains, but deformable media

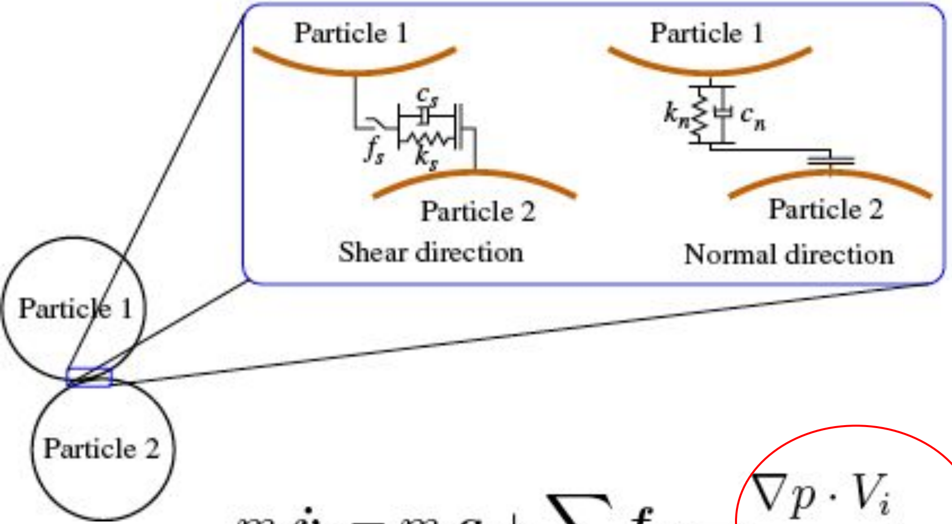
$$\frac{\partial p}{\partial t}=\frac{1}{\beta\phi}\nabla\cdot\left[\frac{k}{\mu}\nabla p\right]-\frac{1}{\beta\phi}\nabla\cdot u_s$$

z+

It can be shown that this formulation is a generalization of:

Wang, 2000
Bechrach et al., 2001 (when neglecting inertia)
Walder & Nur, 1984
Snieder & van der Beukel, 2004
Samuelson et al.., 2009

Adding the grains



$$m_i \dot{\boldsymbol{v}}_i = m_i \boldsymbol{g} + \sum_j \boldsymbol{f}_{ij} - \frac{\nabla p \cdot V_i}{1-\phi}$$

$$I_i \dot{\boldsymbol{w}}_i = \sum_j \boldsymbol{R}_{ij} \times \boldsymbol{f}_{ij}$$

Linear and angular momentum of grain i:

Normal force on grain i:

Elastic repulsive force

Viscous damping

$$\boldsymbol{f}_{ij}^n = \left[k_n \left(R_i + R_j - r_{ij} \right) - \gamma_n m \left(\dot{\boldsymbol{r}}_{ij} \cdot \hat{\boldsymbol{n}} \right) \right] \hat{\boldsymbol{n}}$$

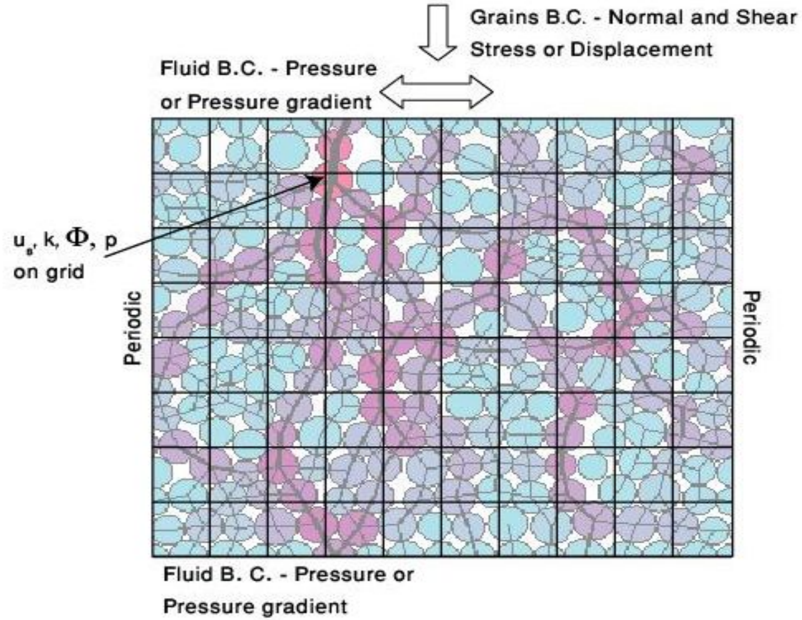
Shear force on grain i:

Elastic shear force

Frictional resistance

$$\boldsymbol{f}_{ij}^s = -\{\min[k_s \Delta s, \mu(\boldsymbol{F} \cdot \hat{\boldsymbol{n}})]\} \hat{\boldsymbol{s}}$$

2-phase 2-scale model



Permeability evolution is given by 3D Carman-Kozeny relationship:

$$k = \frac{k_c(1+2\phi)^2}{(1-\phi)^2}$$

Solid deformation changes the fluid pressure via the divergence in solid velocity

$$\nabla \cdot u_s$$

And the local geometry as expressed by the porosity, permeability

$$\phi \text{ , k}$$

The fluid pressure gradients ∇P act as a force affecting the solid grain motion.

End-member cases of fluid flow

- We consider a simple **pore-fluid** equation including **compaction source and darcian diffusion** (Goren et. al., 2010, 2011).

DARCIAN DIFFUSION

$$\frac{\partial P}{\partial t} - \frac{1}{\beta \Phi \eta} \nabla \cdot [k \nabla P] + \frac{1}{\beta \Phi (1 - \Phi)} \frac{\partial \Phi}{\partial t} = 0.$$

DILATIVE SOURCE

- Where **P(x,t)** is the **pore pressure**, **β** is the **adiabatic fluid compressibility**, **ϕ** is the **porosity**, **η** is the **viscosity of the fluid** and **k** is the **permeability**.

Diffusive End Member:

- Following is the **diffusive end member**, with **initial and boundary conditions** $\frac{\partial P}{\partial t} - \frac{1}{\beta \Phi \eta} \nabla \cdot [k \nabla P] = 0.$ ⟵ **I**

IC: $P(x,0) = 0$ & **BC:** $P(0,t) = P(L,t) = \dot{P}_0 t$

- Plugging in the solution to Eqn **I** in a Mohr Coulomb Failure criterion

$$P_{boundary} = \dot{P}_0 t = \sigma_n - \sigma_T / \mu + \frac{L^2 \dot{P}_0}{8D}$$

- $\mathbf{P_{boundary}}$ is the injected pressure during failure, $\boldsymbol{\sigma_n}$ is the normal stress, $\boldsymbol{\sigma_T}$ is the shear stress, **μ** is the static friction coefficient, **L** is the length of the domain, **D** is the hydraulic diffusivity of the medium and $\dot{P}_0$ is the rate of injection.

Dilative End Member:

- Following is the **dilative end member**

$$\frac{1}{\beta\Phi\eta}\nabla\cdot[k\nabla P]+\frac{1}{\beta\Phi(1-\Phi)}\frac{\partial\Phi}{\partial t}=0. \longleftarrow \textbf{II}$$

- We restructure the source term w.r.t the **strain rate** $\dot{h}/h$

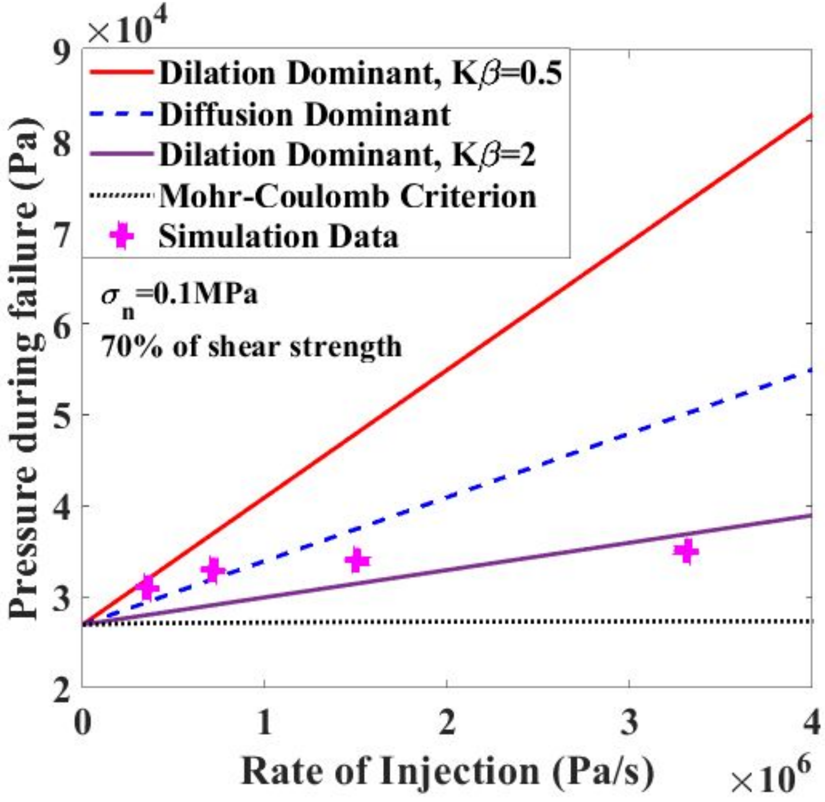
$$\frac{1}{\Phi(1-\Phi)}\frac{\partial\Phi}{\partial t}=\dot{h}/h$$

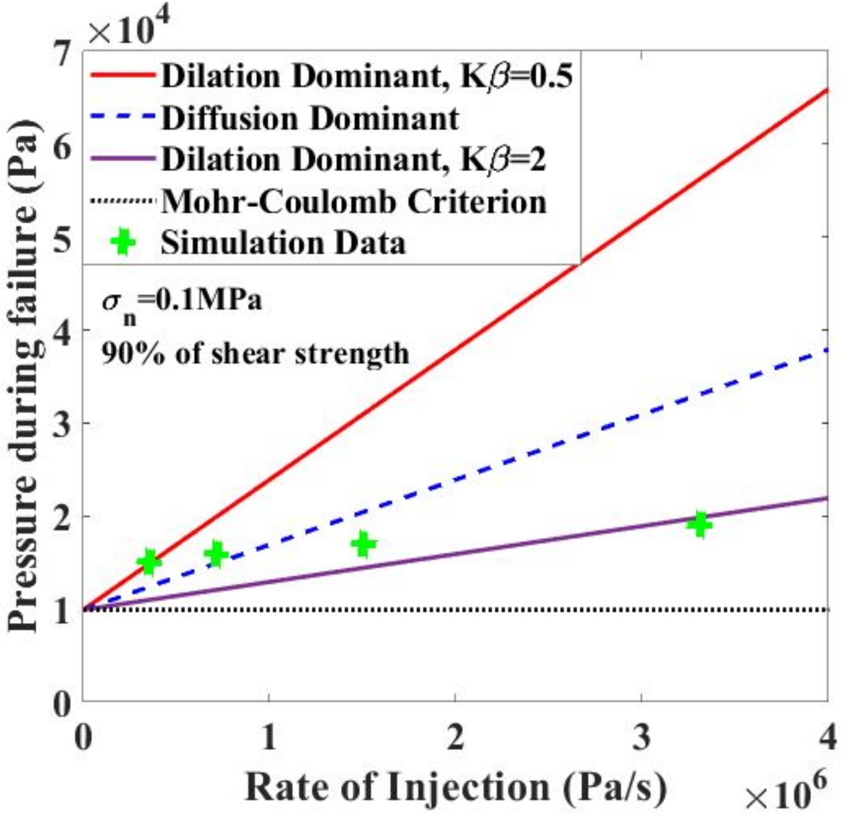
- Plugging in the solution with the same initial and boundary conditions as discussed above to Eqn **II** in a Mohr Coulomb Failure criterion

$$P_{boundary}=\dot{P}_o t_s=\sigma_n-\sigma_T/\mu+\frac{L^2}{8D}\frac{\dot{P}_o}{K\beta}$$

- **K** is the Young's modulus of the grain packing and **β** is the adiabatic fluid compressibility.

Supplementary Results





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