Micromechanics modeling of fault stability under the influence of fluid pressure changes

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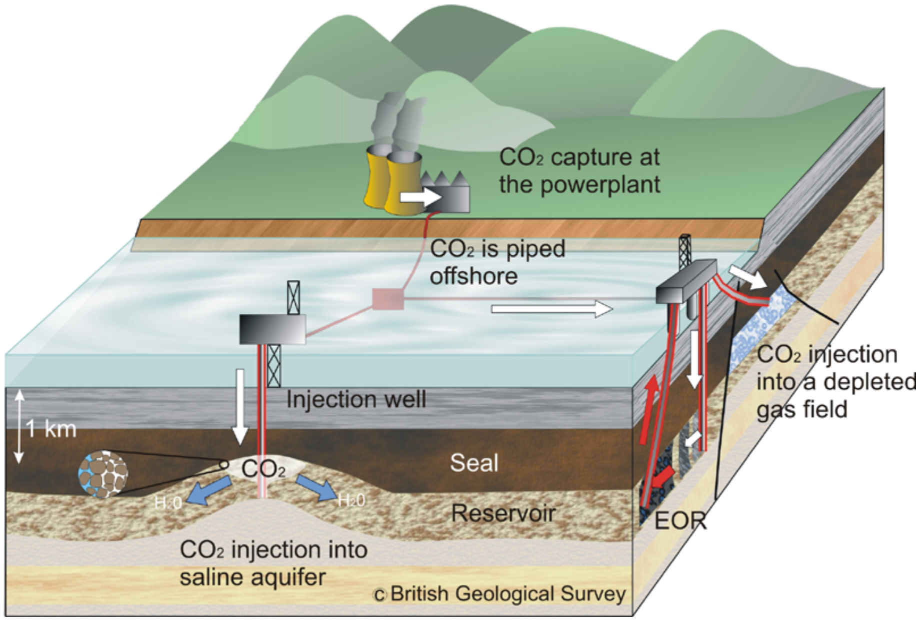
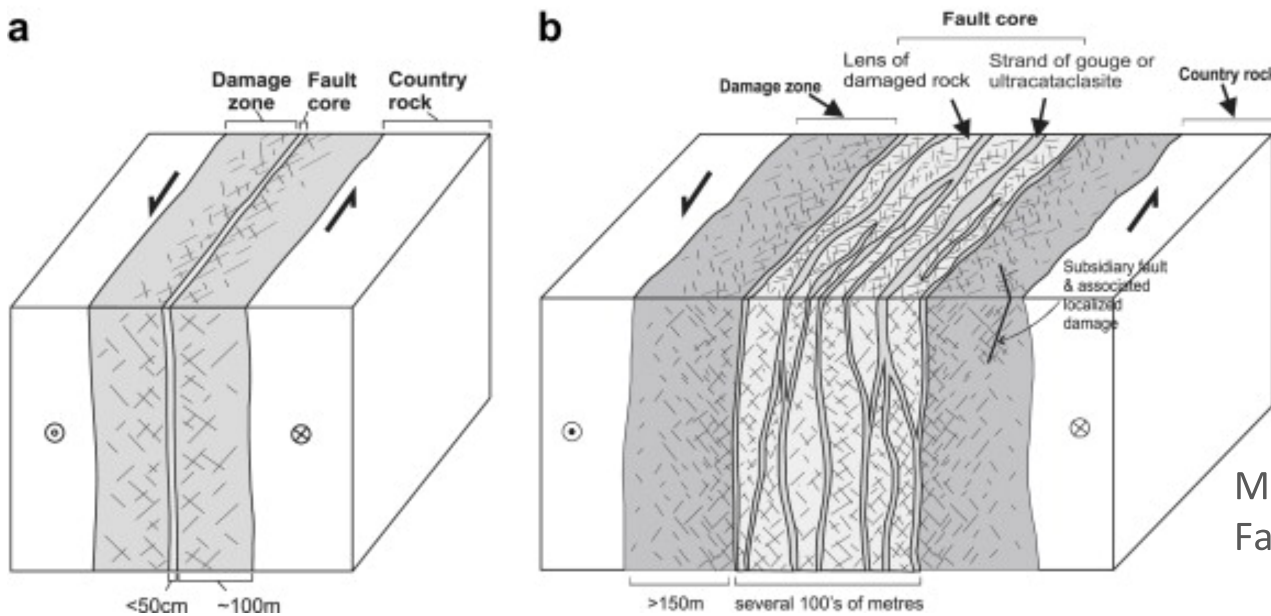
Motivation

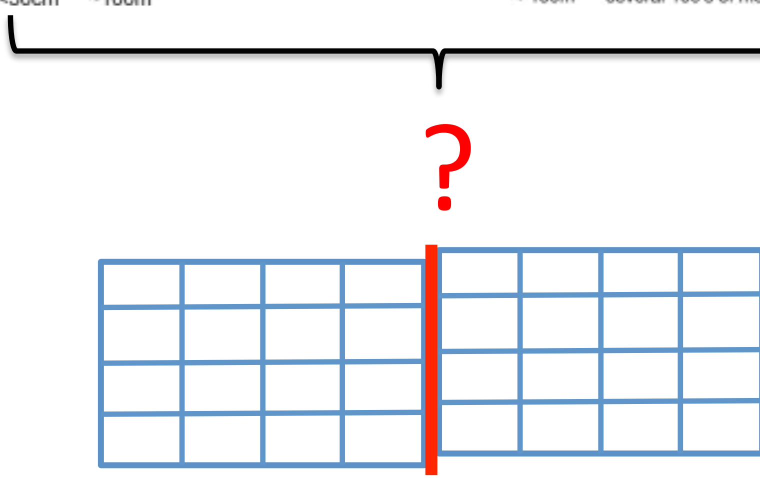
- Induced seismicity
  - The role of pore pressure in faulting
  - Evaluation of fault stability
- Landslides



Geological faults have complex structures

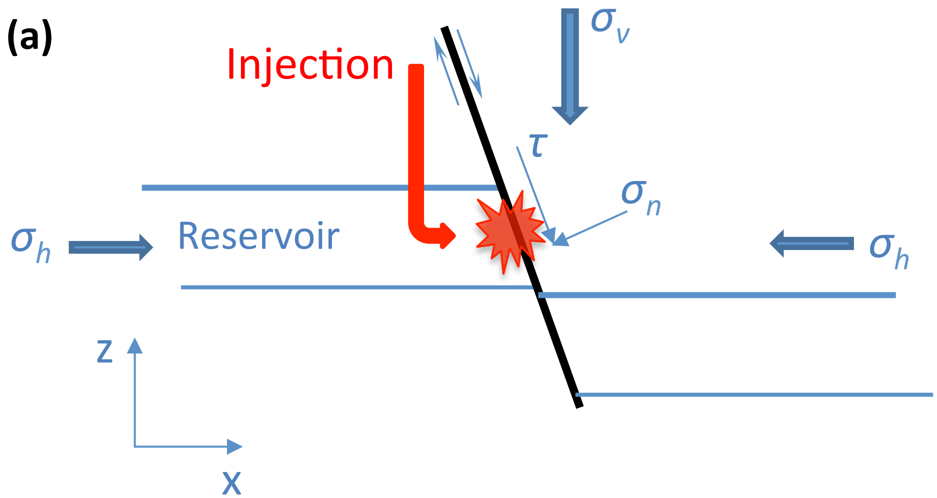


Mitchell and Faulkner, 2009



Reservoir scale coupled hydro-geomechanical modeling

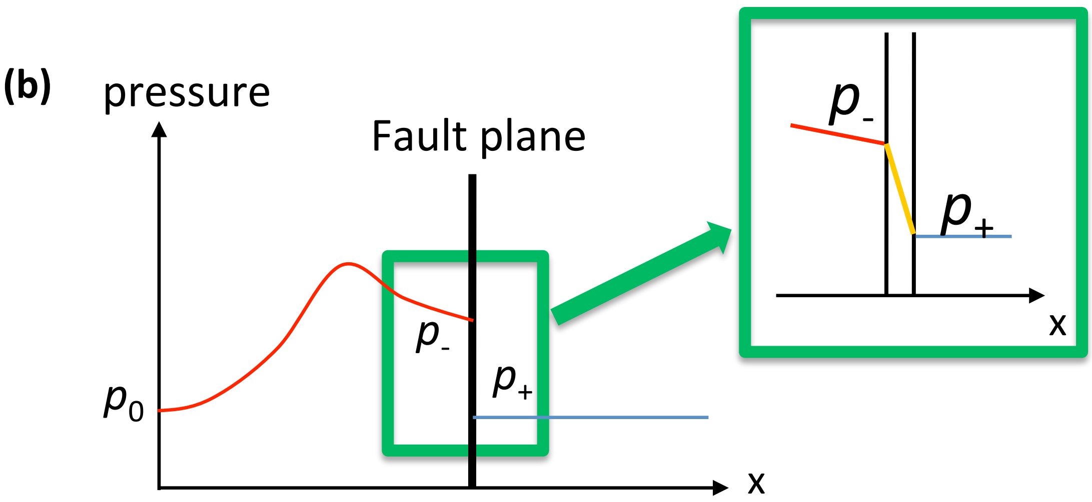
Fault stability criterion



Effective stress principle

$$\boldsymbol{\sigma}' = \boldsymbol{\sigma} - \alpha p \mathbf{I}$$

$$|\boldsymbol{\tau}| \le \mu |\sigma'_n| + c_0$$

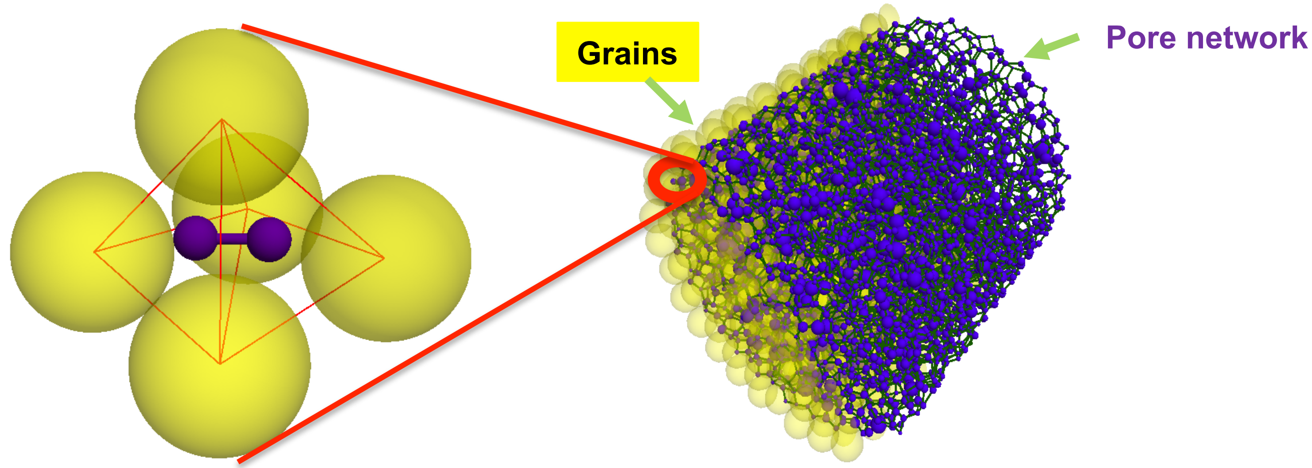


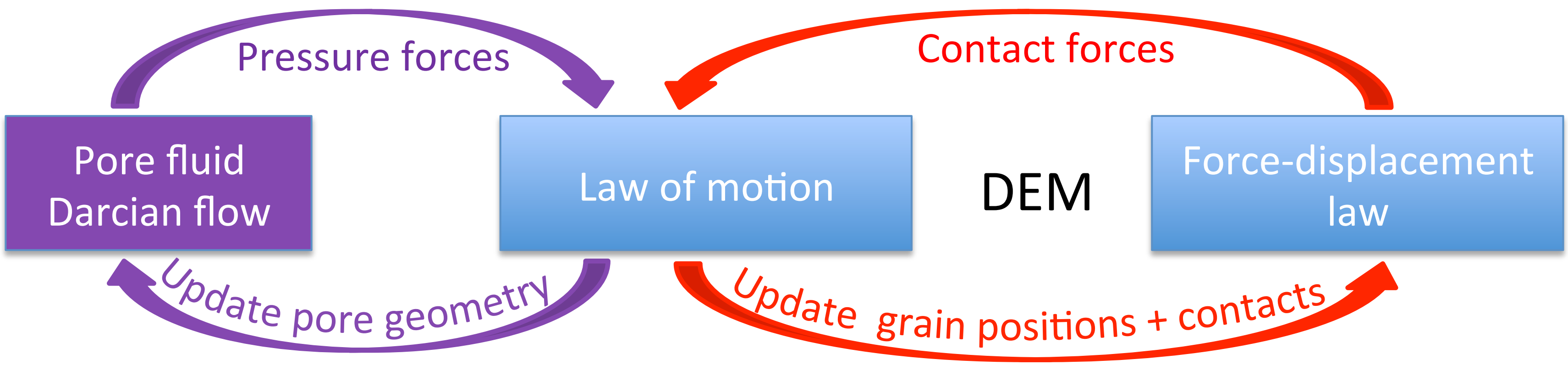
Sealing fault

Which pressure should be used in the Coulomb failure criterion?

Micromechanical modeling

Discrete Element Model ⟷ Pore network flow





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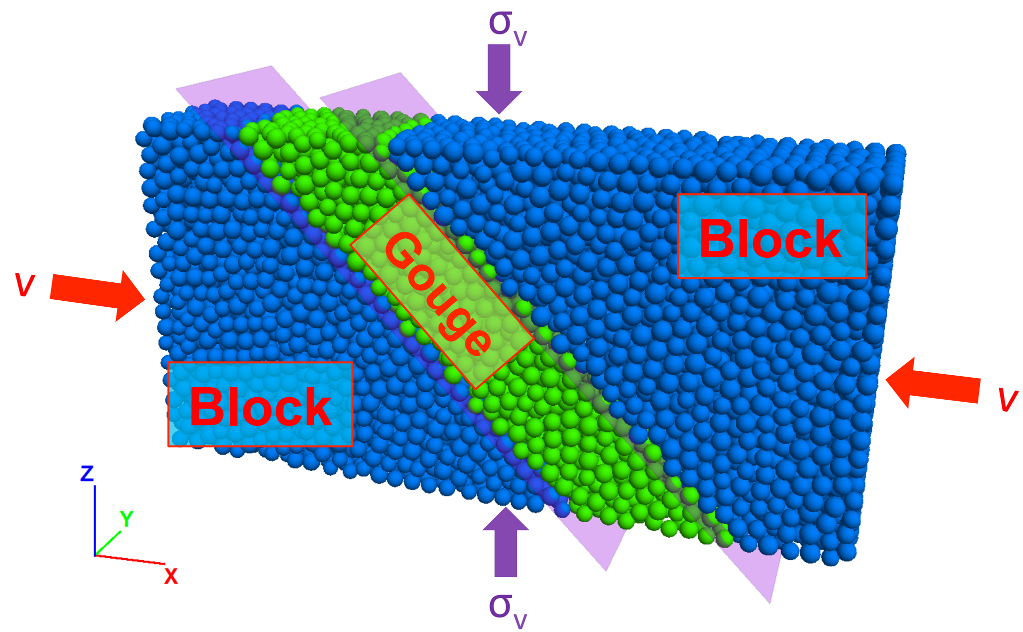
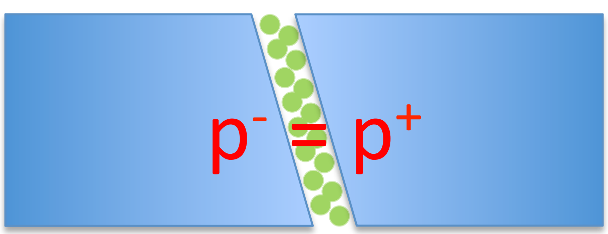
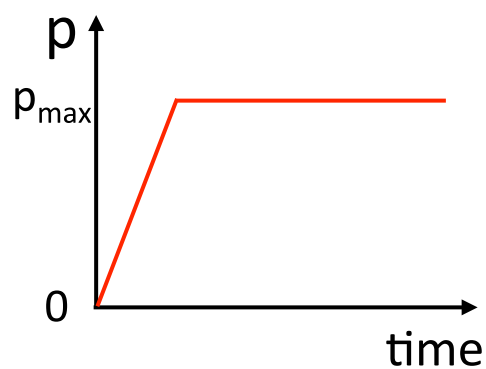
A block-and-gouge model

Fagereng et al. 2011

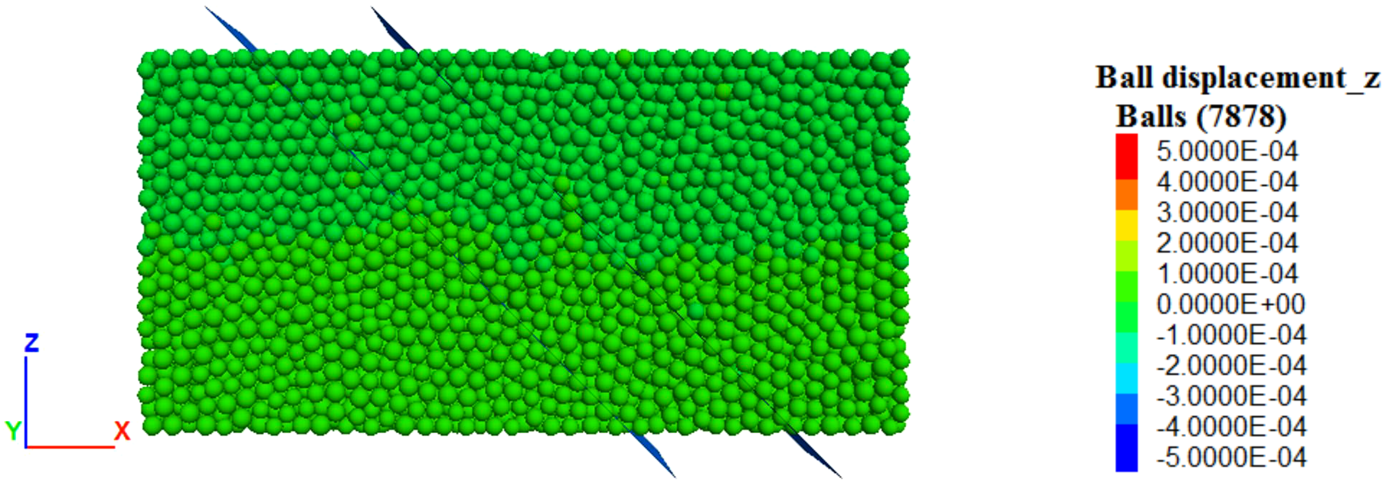




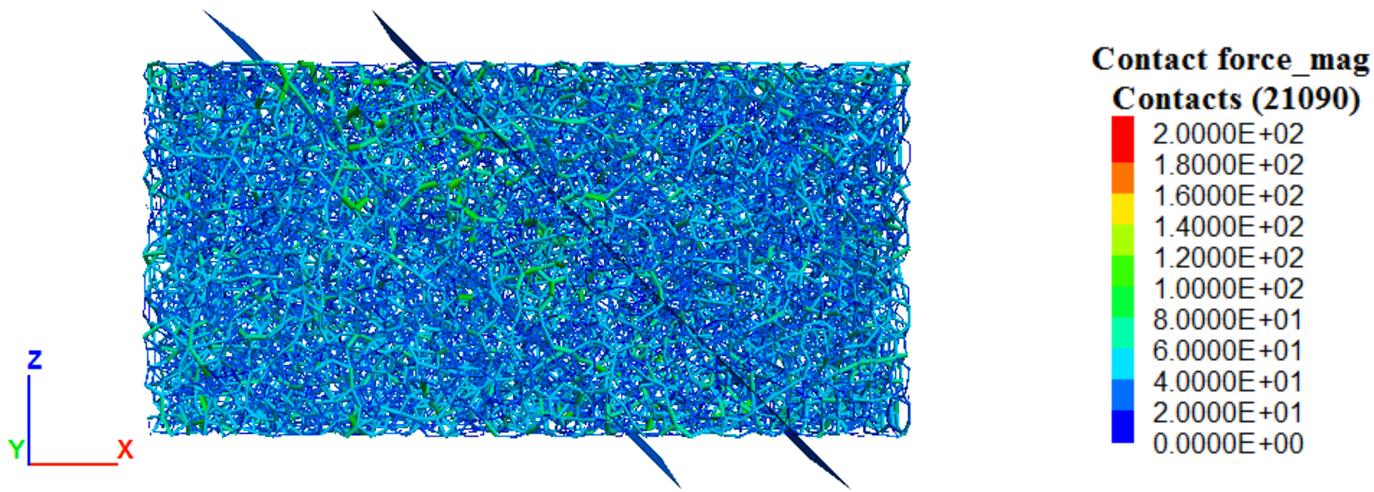


L_x = 8 cm
L_y = 1.6 cm
L_z = 4 cm
T_{gouge} = 1.2 cm
R_{avg} = 0.1 cm
σ_v = 10 MPa
V = 0.000325 m/s

Fault failure by mechanical loading

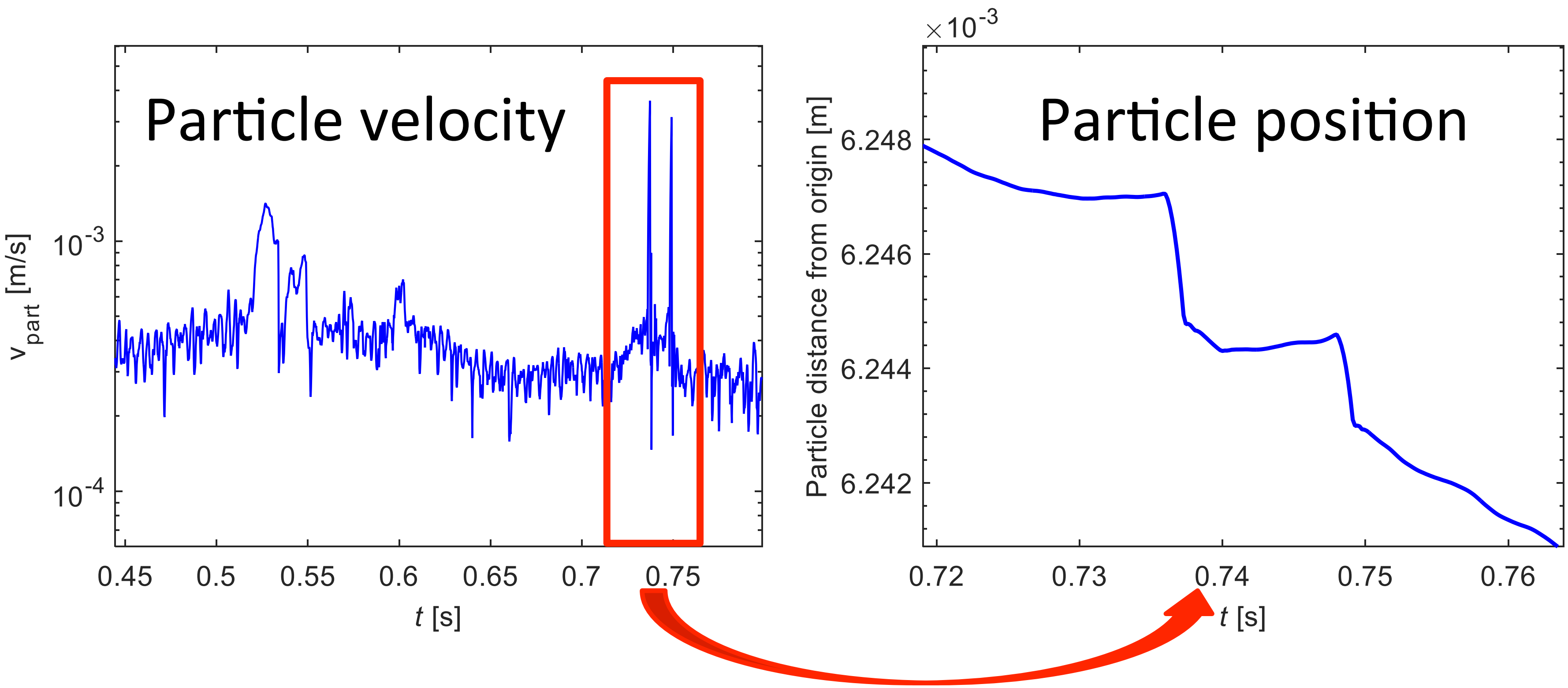


t = 0.00



t = 0.00

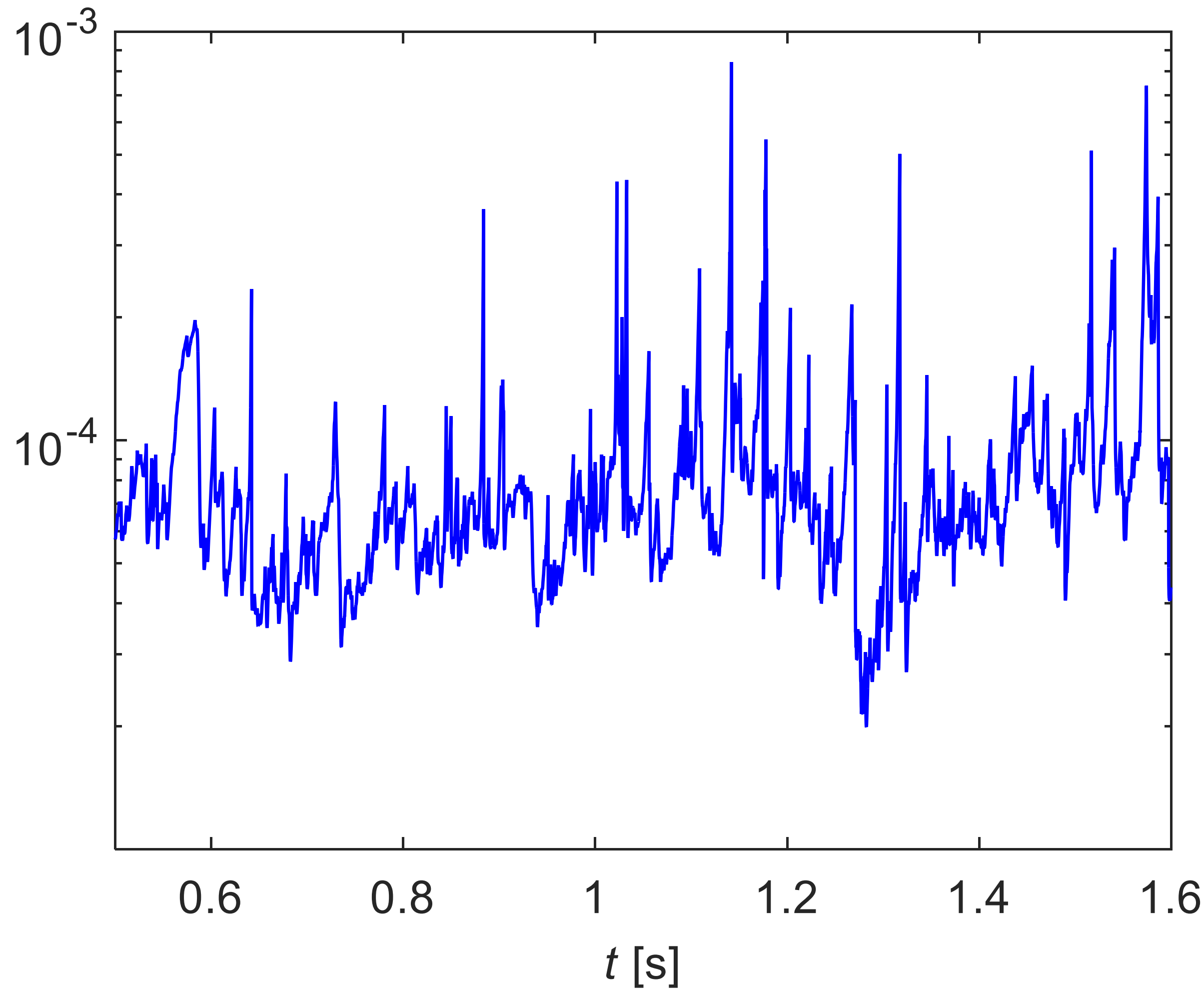
Individual particle velocity and trajectory



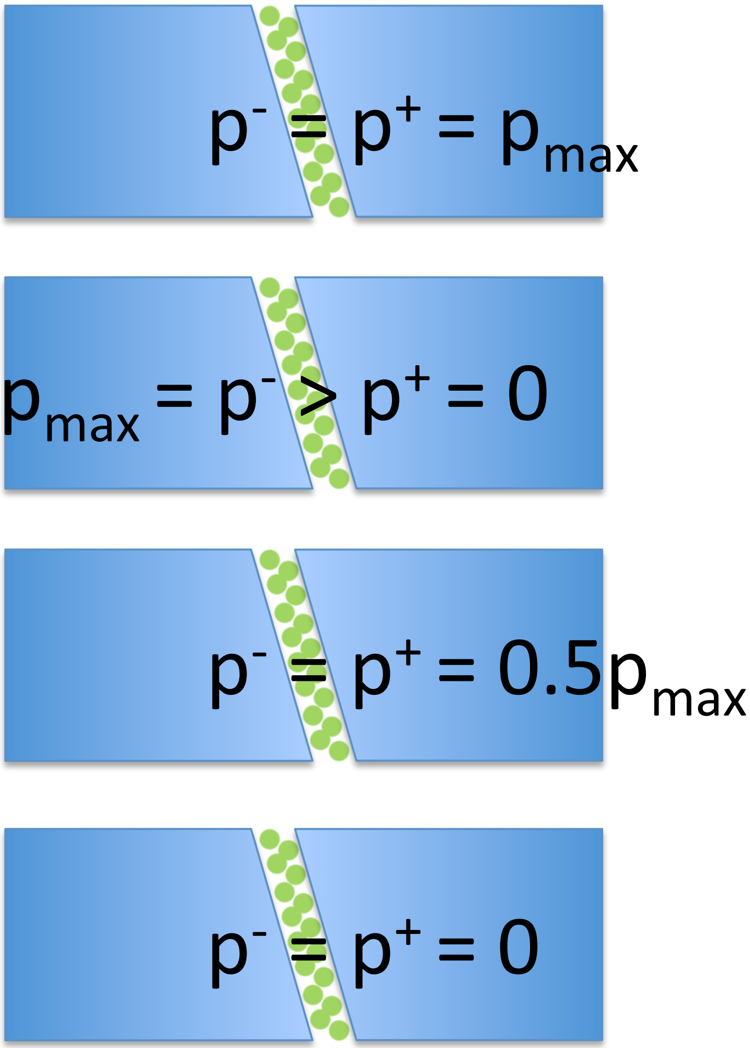
Intermittent behavior

Micromechanical response of the gouge layer

Total kinetic energy [J]



Comparing different pressurization scenarios



Four scenarios:

$p = 0 \rightarrow p_{max}$ until t_1

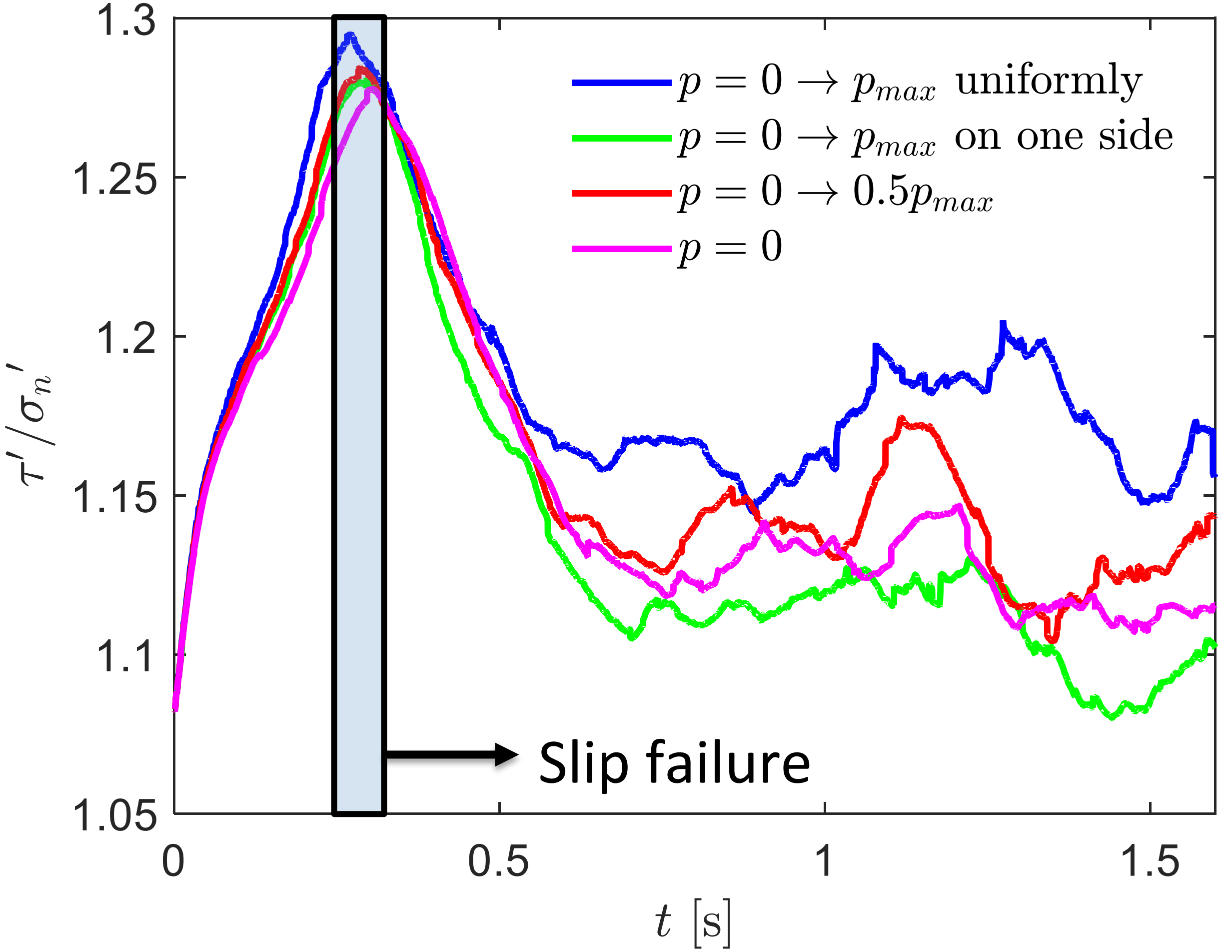
$p = 0 \rightarrow p_{max}$ until t_1 but only on the negative side

$p = 0 \rightarrow 0.5{*}p_{max}$ until t_1

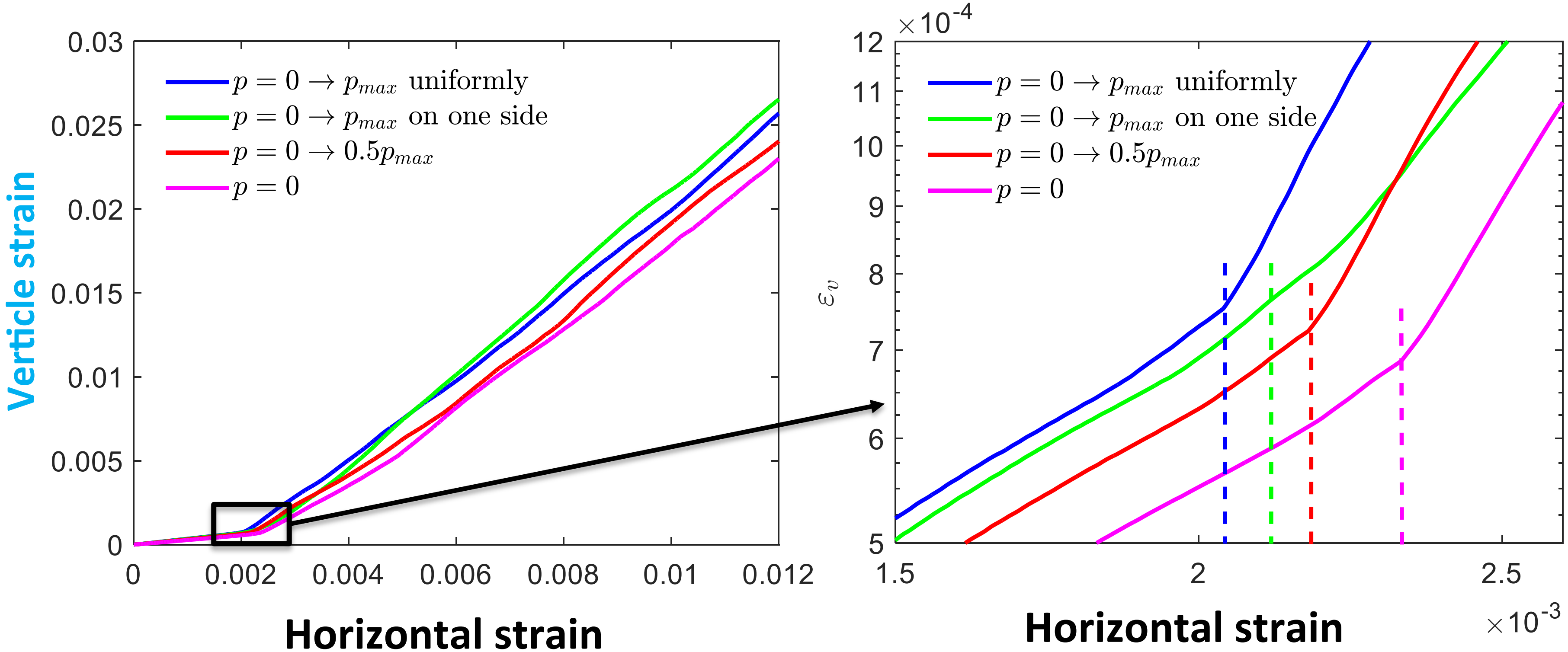
$p = 0$ ("dry")

Slip weakening behavior of the gouge layer

$$\left[\frac{\text{Shear stress}}{\text{Normal stress}}\right]_{\text{eff}}$$



Macroscale onset of failure



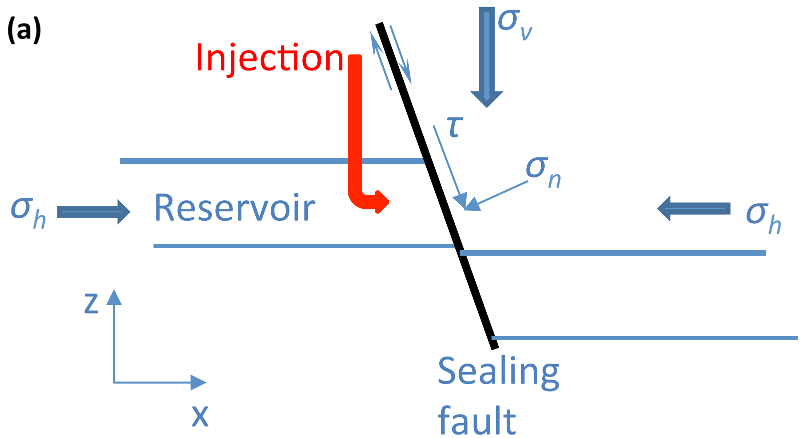
1. Higher pressure → earlier onset of slip
2. When pressure is larger on one side than the other, neither the maximum nor the arithmetic average pressure is suitable for evaluation of the Coulomb failure criterion

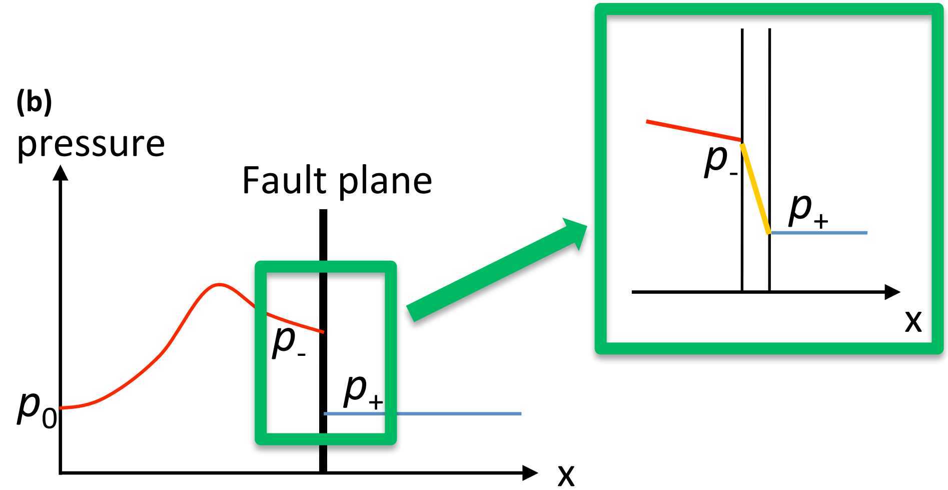
Conclusions and future work

- A coupled DEM and pore-network flow model developed
- Gouge layer slip failure characterized by local-scale stick-slip dynamics
- Pressure imhomogeneity: the CFC cannot be simply evaluated using the max. or the average pressure for the boundary scenario considered
- Future work – additional boundary scenarios; extension to two-phase flow and fracturing

Thank you!

Failure criterion for a sealing fault





Effective stress principle

$$\boldsymbol{\sigma}' = \boldsymbol{\sigma} - \alpha p \mathbf{I}$$

$$|\boldsymbol{\tau}| \le \mu |\sigma'_n| + c_0$$

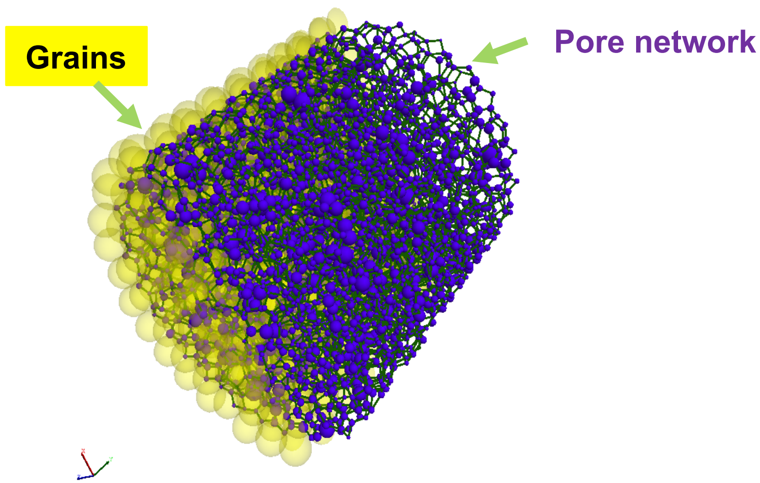
$$\boldsymbol{\sigma}'_- \cdot \mathbf{n} + \alpha p_- \mathbf{I} = \boldsymbol{\sigma}'_+ \cdot \mathbf{n} + \alpha p_+ \mathbf{I}$$

$$\tau_f \le \mu \cdot \min\left(|\boldsymbol{\sigma}'_- \cdot \mathbf{n}|, |\boldsymbol{\sigma}'_+ \cdot \mathbf{n}|\right) + c_0$$

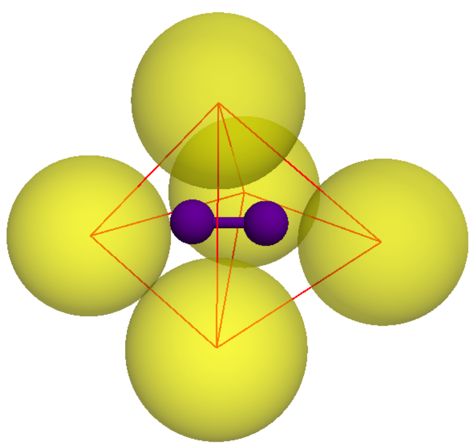
$$p_f \le \max(p_-, p_+)$$

Jha and Juanes, 2014

A micromechanics model for hydro-geomechanic coupling



Two interacting, overlapping networks for the grains and pores



Discrete Element Method (DEM)

$$m_i \ddot{\mathbf{x}}_i = \sum_j \mathbf{F}_j^c + \sum_n \mathbf{F}_n^p \qquad \mathbf{I}_i \ddot{\boldsymbol{\theta}}_i = \sum_j \mathbf{M}_j$$

+

Pore-Network Darcy Flow

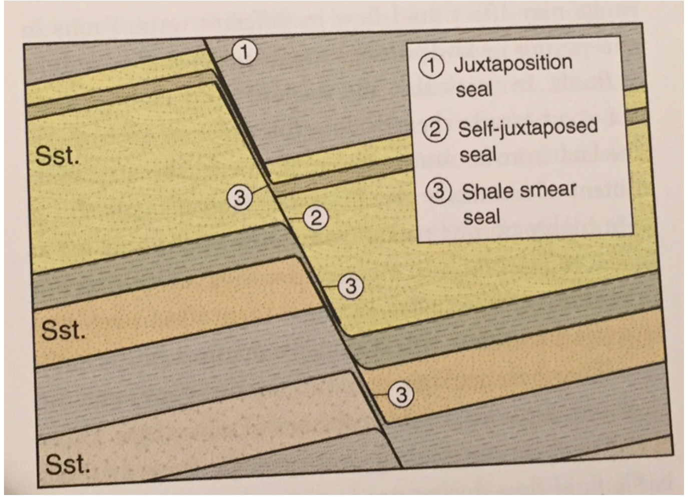
$$\delta p = \frac{K_f}{V_p}\left(-\delta V_p - \sum_j q_j \delta t\right)$$ **Explicit scheme for pore pressure**

$$q_j = C_j\left(\frac{p - p_j}{l_j}\right)$$ **Darcy's Law**

Two-way coupling between the deformation of the solid matrix and the fluid pressure

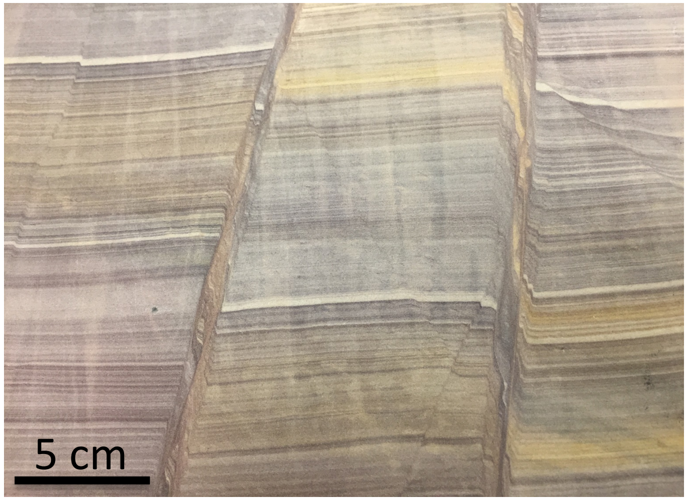
Some faults are sealing

- Juxtaposition
- Cataclasis
- Cementation/diagenetic effects
- Clay and shale smearing



Fossen 2010

Fagereng et al. 2011



Time scales

- Pore pressure diffusion $t_p = d^2 / D_h$ $D_h = k/\mu \beta_w$

- Pore deformation $t_d = d_p / v$

$d = 0.001\ m$ $d_p = 0.1 d$

$k = 1 \times 10^{-9}\ m^2$

$\beta_w = 4 \times 10^{-10}\ Pa^{-1}$

$v = 1 \times 10^{-4}\ m/s$

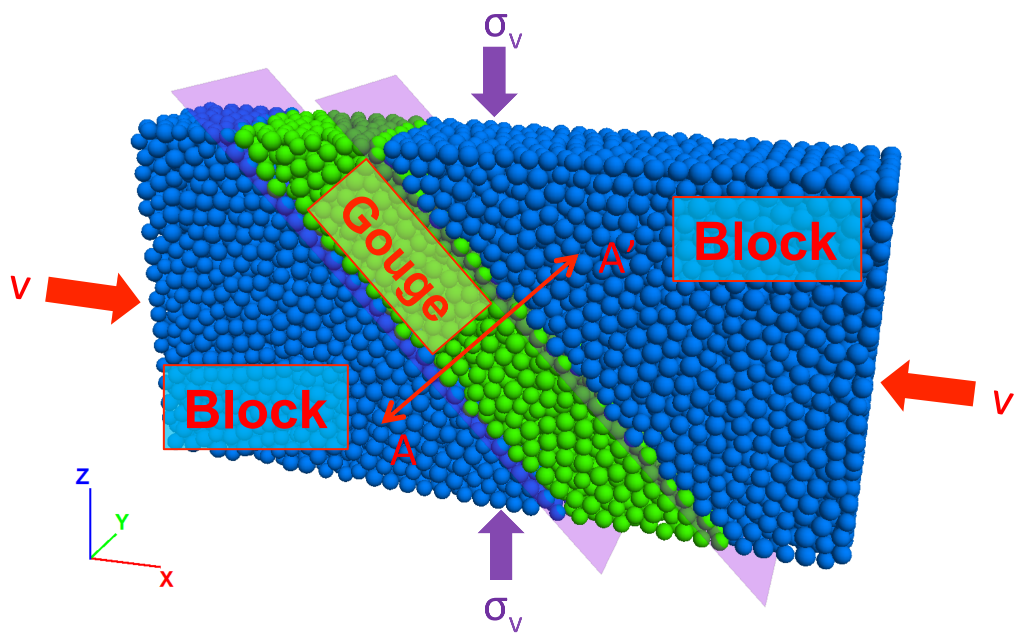
$t_p \sim 10^{-10}\ s$

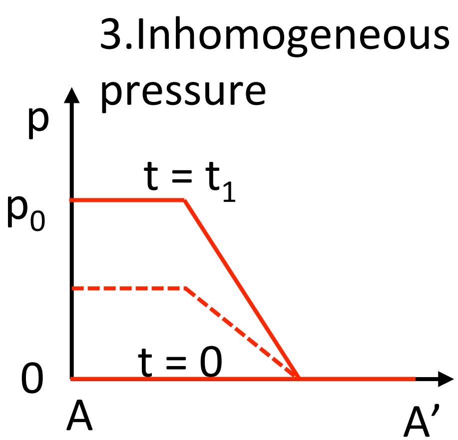
$t_p \sim 1\ s$

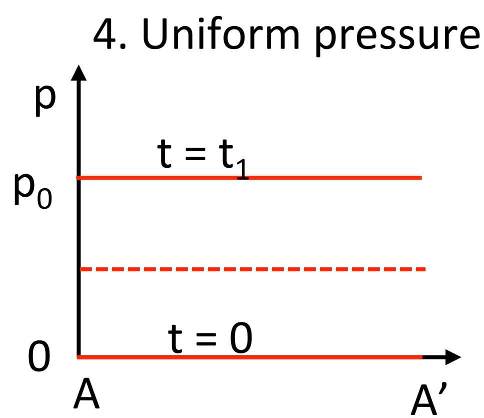
A block-and-gouge model

Four scenarios:

1. $p = 0$ (dry)
2. $p = 0 \rightarrow 0.5{*}p_{max}$ until t_1
3. $p = 0 \rightarrow p_{max}$ until t_1 but only on the negative side
4. $p = 0 \rightarrow p_{max}$ until t_1







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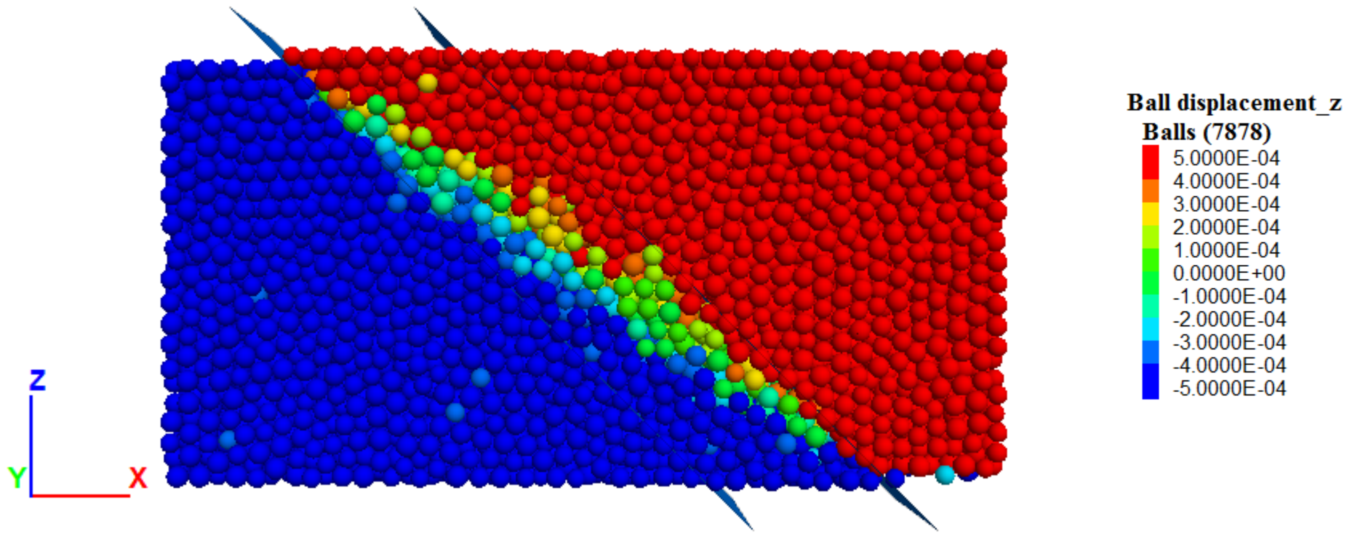
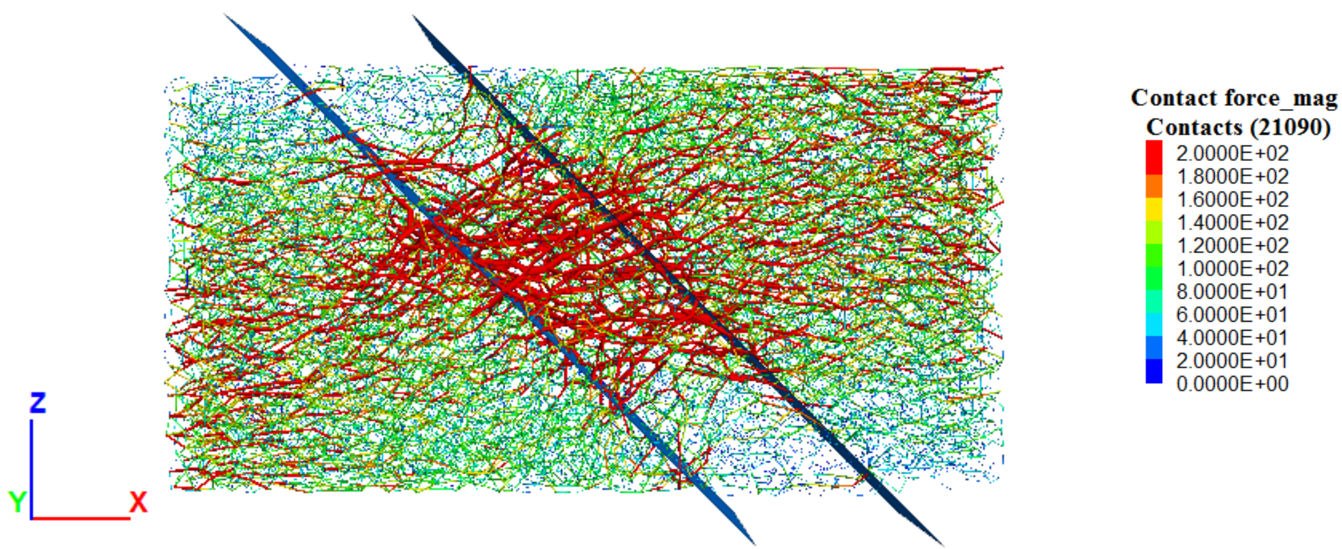
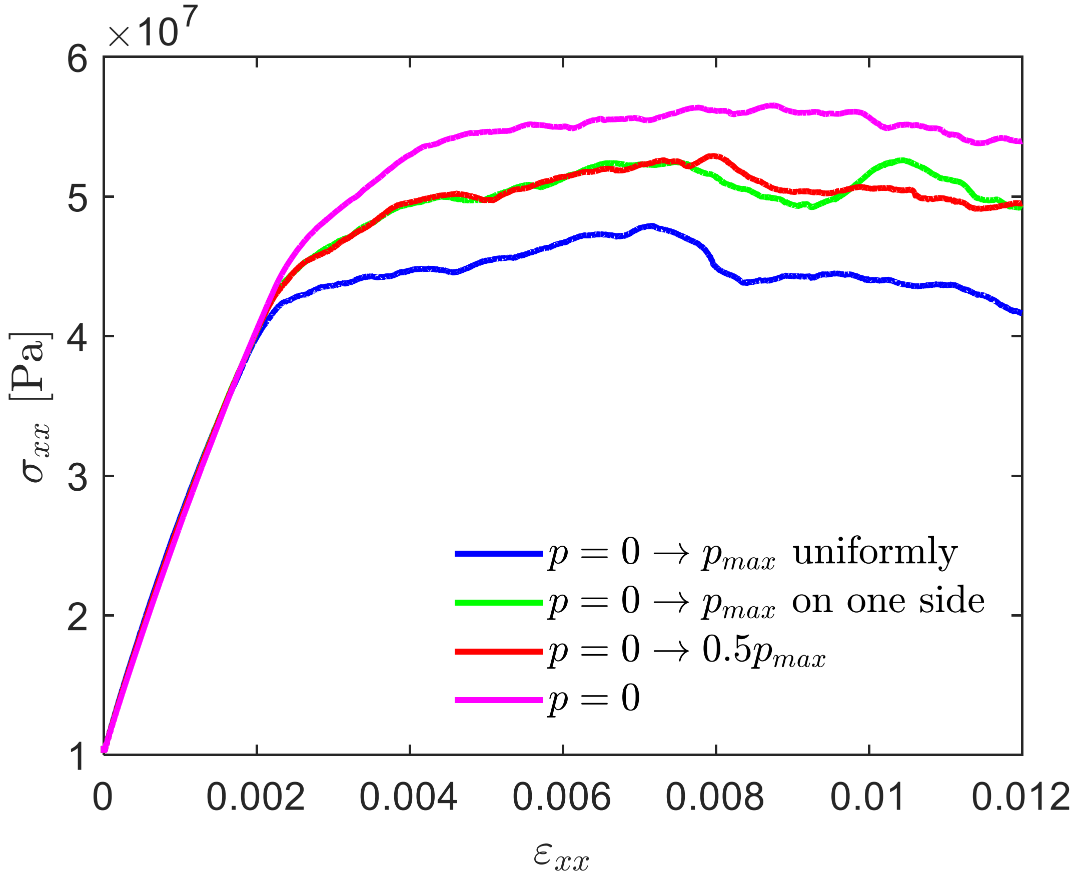

Ball displacement_z
Balls (7878)
5.0000E-04
4.0000E-04
3.0000E-04
2.0000E-04
1.0000E-04
0.0000E+00
-1.0000E-04
-2.0000E-04
-3.0000E-04
-4.0000E-04
-5.0000E-04
Z
Y
X


Contact force_mag
Contacts (21090)
2.0000E+02
1.8000E+02
1.6000E+02
1.4000E+02
1.2000E+02
1.0000E+02
8.0000E+01
6.0000E+01
4.0000E+01
2.0000E+01
0.0000E+00
Z
Y
X

Horizontal stress evolution



Stress calculation

- microstress

$$\boldsymbol{\sigma}^{c} = \frac{1}{V_{\sigma}} \sum_{k} \mathbf{x}^{c,k} \otimes \mathbf{f}^{c,k}$$

- Averaging over the gouge layer

$$\bar{\boldsymbol{\sigma}} = \left\langle \boldsymbol{\sigma}^{c} \right\rangle_{gouge}$$

$\varepsilon_v = \Delta L_z / L_z$

Verticle strain