FLUID INJECTION EFFECT ON FRACTURE PROPAGATION NEAR AN UNDERGROUND DRIFT

Mohammad Youssef Fallah Soltanabad,
Amade Pouya, Laurent Brochard, Lina-María Guayacán-Carrillo,
Christophe De Lesquen, Minh Ngoc Vu
Introduction

- Excavation of underground galleries in the Callovo-Oxfordian claystone

Fracture network around the tunnel wall (EDZ)

Mechanical and hydraulic disturbances (creation of damaged and fractured zones)

- Over the long term: additional stress from gases, particularly hydrogen, resulting from corrosion of the metals used in the casing of radioactive waste packages

Armand et al. 2013
Fracture propagation from the extremity of existing fractures under fluid injection action

Simple cases of existing fractures around the gallery

Initial conditions:
- \( \sigma_H, \sigma_V \): in-situ stresses
- \( p_0 \): initial pore pressure

Load actions:
- \( p_f \): injected fluid pressure
- \( \sigma_n = -p_f \): fluid mechanical action

Isotropic stress

Anisotropic stress
Theoretical framework

Rock behavior $\rightarrow$ Poroelastic medium

Hydraulic constitutive model

$$C_M \frac{\partial p}{\partial t} = \text{div}(K\nabla p) + (-\rho_f b \frac{\partial v}{\partial t})$$

$$K = \frac{\rho_f}{\mu} k \quad C_M = \frac{\rho_f}{M}$$

Mechanics constitutive model

$$\text{div}\sigma(x) + f^v(x) = 0$$

$$\sigma(x) = \sigma^i(x) + C(x, \epsilon(x), D) : [\epsilon(x) - \epsilon^r(x)]$$

$$\sigma^i = -bp\delta$$

Numerical modeling

- Disroc code (Fracsima – A. Pouya)
- Finite Element Code enriched with joint elements
- Coupled thermo-hydro-mechanical phenomena in materials and structures in the presence of fracturing
- Analyze fracture propagation
- Under the effect of incompressible fluid injection
- Evaluate the equivalence of numerical modeling results and analytical solutions (Tada et al. 2000)

https://www.fracsima.com/DISROC
Cohesive fracture model

Damage-Plasticity of rock joints
(Pouya & Bemani 2014)

\[ \sigma = (1 - D) \ k \ (u - u^P) \]

Plasticity and damage criterion:
\[
F(\sigma, D) = \tau^2 - \sigma_n^2 \tan^2 \phi + 2g(D)\sigma_c\sigma_n - g^2(D)C^2
\]
\[ g(D) = (1 - D)(1 - \beta \ln(1 - D)) \]

Traction-Separation law for different values of the parameter \( \beta \).

Evolution of the criterion from the intact condition (green) to a frictional law (blue) during the damage process (red arrows)

Comparison CZ-Fracture- Linear Elastic Fracture Mechanics - Fracture in a half-space

\[ K_{IC} = \frac{E}{\sqrt{1 - \nu^2}} \left[ \frac{1}{2} + \beta (\beta + 1) \right] \sigma_R^2 k_n \]

\[ \sigma_R = \frac{2}{\pi L_j} K_{IC} \]

Mesh size \( L_j \ll L_{zp} \)

Mesh size \( L_j \gg L_{zp} \)

Claystone: \( L_{zp} \approx 2 \text{ mm} \)

\[ L_{zp} = \frac{\pi}{8} \cdot \frac{E}{k_n \cdot (1 - \nu^2)} \cdot \left[ \frac{1}{2} + \beta (\beta + 1) \right] \]
**Geometries and parameters**

### Isotropic case

\[ \sigma_v = -12.55 \, \text{MPa} \]

\[ \sigma_h = -12.55 \, \text{MPa} \]

### Anisotropic case

\[ \sigma_v = -12.55 \, \text{MPa} \]

\[ \sigma_h = -16.1 \, \text{MPa} \]

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#### Mechanical parameters applied to the pre-existing fracture

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_n )</td>
<td>( 3 \times 10^5 , \text{MPa/m} )</td>
</tr>
<tr>
<td>( k_t )</td>
<td>( 3 \times 10^5 , \text{MPa/m} )</td>
</tr>
<tr>
<td>( e )</td>
<td>( 0.00001 , \text{m} )</td>
</tr>
<tr>
<td>( \sigma_R )</td>
<td>( 5.05 , \text{MPa} )</td>
</tr>
<tr>
<td>( C )</td>
<td>( 50 , \text{MPa} )</td>
</tr>
<tr>
<td>( \varphi )</td>
<td>( 27^\circ )</td>
</tr>
<tr>
<td>( h_r )</td>
<td>( 1 )</td>
</tr>
<tr>
<td>( \delta )</td>
<td>( 0.1 )</td>
</tr>
<tr>
<td>( \delta' )</td>
<td>( 1 )</td>
</tr>
<tr>
<td>( k_{0t} )</td>
<td>( 3 \times 10^4 , \text{MPa/m} )</td>
</tr>
<tr>
<td>( k_{0n} )</td>
<td>( 3 \times 10^4 , \text{MPa/m} )</td>
</tr>
</tbody>
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**Hydraulic conductivity of pre-existing fracture is** \( 2.7 \times 10^{-17} \, \text{m}^3 \)

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**The mechanical parameters for the undamaged zone are the same as the pre-existing fracture except for the following parameters:**

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>( e )</td>
<td>( 0.001 , \text{m} )</td>
</tr>
<tr>
<td>( k_{0t} )</td>
<td>( 300 , \text{MPa/m} )</td>
</tr>
<tr>
<td>( k_{0n} )</td>
<td>( 300 , \text{MPa/m} )</td>
</tr>
</tbody>
</table>

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**The hydromechanical parameters of the Rock (COx):**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E )</td>
<td>( 5200 , \text{MPa} )</td>
</tr>
<tr>
<td>( \nu )</td>
<td>( 0.3 )</td>
</tr>
<tr>
<td>( k )</td>
<td>( 2.7 \times 10^{-20} , \text{m}^2 )</td>
</tr>
<tr>
<td>( C_M )</td>
<td>( 2.8 \times 10^{-4} , \text{MPa}^{-1} )</td>
</tr>
<tr>
<td>( b )</td>
<td>( 0.8 )</td>
</tr>
</tbody>
</table>
Results - Effect of stress anisotropy

\[ \sigma_H = \sigma_V \]

Isotropic stress field

\[ \sigma_H > \sigma_V \]

Anisotropic stress field

Geometry of the fracturing, for the cases of isotropic and anisotropic in-situ stresses.
Results - Effect of stress anisotropy

- Purely mechanical loading
- Approximation of a short time scale
- Les propagation in the anisotropic case.
- Propagation toward the radial path
- The propagation is primarily controlled by fluid pressurization
Results - Effect of fluid flow

- Stationary flow and transient flow
- The hydro-mechanical couplings
- The hydromechanical coupling $H \rightarrow M$
- The stationary calculation: Less propagation than the mechanical calculation
- The transient calculation: The effect of time of diffusion, the same propagation as for the mechanical calculation
Conclusion

- The in-situ stress anisotropy essential for reactivation and propagation
- The fracture follows the radial path favored by the fluid loading
- The poromechanical coupling in the rock exposed to the stationary pressure field tends to act against fracture propagation
- For transient conditions, before any significant fluid diffusion (1s) the propagation is even smaller than for the stationary case, but after 1 day (diffusion in the fracture but not in the rock) one recovers the simple mechanical case
On-going work and perspectives

- Unsaturated flow and poromechanical coupling in the fracture
- Dissolution of gas in the liquid phase and advective transport

- Criterion for fracture propagation in unsaturated porous medium?
- Crack propagation in viscoplastic?
- Rate of gas production?
References


Thank you for your attention