Fracture static elastic properties inferred from flow measurements

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Motivation – Unified Rock Physics Model

• A model coupling fluid flow and elastic properties in rocks

Adopted from Li et al. (2015)
Motivation – Importance of Fractures

- Presence of fractures enhances material and energy exchange
- Key components in geological and sub-surface engineering
  - Unconventional hydrocarbon production
  - Geothermal energy extraction
  - Hydrogeological phenomena

Image: iogsolutions.com
Image: marine.gov
Image: geothermalworldwide.com
Motivation – Elasticity Measurements

• Variations between dynamic and static elastic parameters in rocks

• Relatively common to obtain dynamic elasticity
  • Seismic survey, acoustic logging, pulse transmission experiments

• Not necessarily straight forward to get static elasticity
  • Direct mechanical measurements unable to conduct in subsurface

💡 Stress-dependent flow properties also reflect fracture elasticity
Background

Implicit linkage between fluid flow and stiffness properties in rough fractures

- Contact areas determines stiffness
- Pore volumes determines fluid flow conductivity

Adopted from Brown (1989)

Adopted from Pyrak-Nolte et al. (2000)
Objectives

To infer for fracture static elastic properties (e.g. compliance, stiffness, compressibility, stress-free areas) from flow measurements

- Using steady-state fluid flow properties of different stress levels
- Develop relation on mechanical characteristics
Workflow

1. Experimental flow measurements on fracture
2. Flow simulation on digitized fracture configurations
3. Inversion for pressure-displacement relationship
4. Inference of fracture static elastic properties
Semi-Rough Fracture Model

\[ P_c = P_f \]

\[ \text{Var}(S_2) = \sigma^2 \]

- \( P_c \) : Confining Pressure
- \( P_f \) : Pore Pressure
- \( P_e \) : Effective Pressure \((P_c - P_f)\)
- \( d \) : Compression Displacement

\( S_1 \mid d = 0 \sigma \)

\( d \) (in factors of \( \sigma \))
Semi-Rough Fracture Model

Increasing effective pressure
- Reduces aperture height
- Increases contact area

$P_c >> P_f$

$P_c$: Confining Pressure
$P_f$: Pore Pressure
$P_e$: Effective Pressure ($P_c - P_f$)
$d$: Compression Displacement

Assuming no surface deformation at uncontacted regions
Stress dependency of flow properties

Aperture distribution

Simulated flow flux field

\[ d = 1.5\sigma \]

\[ d = 2.5\sigma \]
Inversion for $d - P_e$ Relation

- By minimizing the discrepancies between measured and simulated permeability
- Correspondence between confining pressure and compression displacement
Inversion for $d - P_e$ Relation

Parametric curve fitting

$$d = a + \sigma_E \ln P_e$$

- Half-joint model assuming exponential-distributed aperture
  
  (Swan, 1983)

$$d = -1.48 \times 10^{-3} + 1.20 \times 10^{-4} \ln P_e$$

* $\sigma_{true} = 2.04 \times 10^{-4} \text{ m}$
Inverted Fracture Elasticity - Stiffness

- Logarithmic increase in rock stiffness

- Substantial difference in rock stiffness under different pressure

- Inverted rock stiffness of several GPa between 5 – 30 MPa effective pressure

\[ \kappa = \frac{\partial P_e}{\partial \epsilon} \]
Inverted Fracture Elasticity - Incompressibility

Benchmarking with published data

- Linear increase in incompressibility against pressure
- Single fracture “softer” than cracks

\[ \frac{1}{\kappa^{-1} - \kappa_s^{-1}} \]

\[ \kappa_s = 70 \text{ GPa} \]

Modified from Walsh and Grosenbaugh (1979)
Summary

With a known fracture topography, we can obtain

- Fracture permeability under compression displacement
  - Numerical flow simulations based on semi-rough model

- A compression displacement – effective pressure relation
  - Inverted from the permeability reduction trend from experiment and simulations

- Fracture static elastic properties
  - Inferred from the inverted mechanical relation
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