Anisotropic Damage Mechanics for Modeling Hydraulic Fracturing in a Layered Naturally Fractured Reservoir

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Hydraulic – Natural Fracture Interaction

• Fundamental phenomenon needed for a better understanding of unconventional wells

• Very complex physics to model ➔ multiple methods are available

• Limited data to validate models ➔ Microseismic is the only volumetric field data that helps validate SOME aspects of this physics
FracGeo’s Approach to Modeling HF-NF

• Use continuum mechanics augmented with discontinuities' modeling to describe the HF-NF interaction

• Use the particle based method Material Point Method (MPM) to resolve the computational challenges.

• Use the Continuous Fracture Modeling (CFM) approach to describe the distribution of natural fractures in the reservoir

• Validate (NOT CALIBRATE) every geomechanical result with available field data (drilling, microseismic, pressure treatment, production, etc.)
Removing Geomechanics from its silos: GMX from drilling to well interference optimization

Torque Comparison

Reservoir **differential stress** and **strain** validated with microseismic data

Geomechanical properties, pore pressure, stresses and natural fractures predicted from surface drilling data and CMSE

**Poroelasticity** for well interference optimization

Fully coupled **Fast Marching Method (FMM)** flow simulator for **pressure depletion**

Geomechanically constrained **3D planar Frac simulator**
Material Point Method (MPM)

• MPM Originated from University of New Mexico & Sandia National Lab

• MPM is a powerful computational technique for solving solid dynamic problems;

• Used by Disney in Frozen and other movies
Material Point Method (MPM)

- Powerful tool developed for solid dynamics problems (Sulsky, Chen & Schreyer, 1994)

- Particle method: discretization into points, called particles

- Particles handle all material information

- Background grid associated with the particles, composed of elements.

- At each time step, particles information are extrapolated to the background grid to solve the equations of motion
MPM Application to HF-NF Interaction

• Explicit Fractures using Fracture Mechanics (FM)
  • CRAMP algorithm for explicit fracture modeling (Nairn, 2003)
  • J-Integral calculation
  • Cohesive zone model

➤ The Continuous Fracture Model (CFM) provides the explicit description of the fractures at different scales

• Continuum Damage Mechanics
  • Anisotropic damage mechanics (ADaM) model (Nairn, Hammerquist, Aimene, 2017)
  • Augments a constitutive law
  • Uses the forth rank damage tensor by Chaboche (1979)

➤ The CFM models and seismic attributes provide the necessary Anisotropic Damage
Explicit Fracture in MPM

- J-Integral for fracture front parameters
  - J integral calculate the energy release rate and fracture-tip stress intensity factors
  - fracture tip parameters used to predict fracture initiation & propagation direction

Stress field around fracture tip
Hydraulic fracturing benchmarks

- Teufel & Warpinski (1987) tests

(Blanton, 1982)
Hydraulic fracturing benchmarks

- Fracture propagation path re-orientation to follow the maximum stress direction

Rock elastic properties

\[ E = 8.4 \text{ GPa} \]
\[ \nu = 0.23 \]
\[ \rho = 2.5 \text{ g/cm}^3 \]

Material toughness

\[ G_c = 2.55 \text{ J/m}^2 \]

Initiation & propagation

Maximum energy release rate & maximum hoop stress

\[ \sigma_h = 4 \text{ MPa} \]

Experimental fracture path from Chen et al. 2010.

Fracture path from MPM simulation

Fracture turning
Anisotropic Damage Mechanics Model (ADaM)

- The material constitutive law is augmented by an anisotropic damage tensor $D$ (Chaboche, 1979):
  \[ \sigma = (I - D) C_0 \varepsilon \]

- $D$ depends on 3 damage variables ($d_n$, $d_{xy}$, $d_{xz}$)

- Damage initiation is controlled by “damage initiation laws” attached to the material & damage propagation is perpendicular to the failure envelope
Damage initiation and propagation

• The damage evolution is determined by three softening laws

\[ T_n = \sigma_n f_n(\delta_n) \quad T_{xy} = \tau_t f_t(\delta_{xy}) \quad T_{xz} = \tau_t f_t(\delta_{xz}) \]

• The area under these softening laws are connected to tensile and shear energies released by propagation of damage.

• Summary
  • Damage parameters are strengths and toughness, along with failure envelop shape.
  • The damage model honors thermodynamics conditions for energy dissipation and have direct correspondence to fracture mechanics of an explicit fracture.
ADaM on general benchmarks tests

- Pre-cracked three-point bending specimen subject to dynamic impact with the eccentricity of $e = 20 \text{ mm}$

Experimental results and FEM predictions (Nishioka et al., 2001)
ADaM on general benchmarks tests

- Pre-cracked three-point bending beam specimen subject to dynamic impact.

ADaM results capture well the mixed mode.
ADaM vs. FM on general benchmarks tests

- Square rod with an initial fracture at 60° loaded in tension.

3D explicit fracture in MPM from Guo and Nairn, 2018

3D damage mechanics in MPM
ADaM on a Layered Rock (Oreo Models)

- Numerical settings
  - Test 11 in AlTammar and Sharma (2017)
  - Perfect interface to match the well-bonded interfaces.

\[ \sigma_z = 32 \text{ psi} \]

Average fluid particles vs. experimental monitoring injection pressure
Isotropic “Oreos”

- Asymmetric height
- Early propagation

- Symmetric height
- Contained fracture
Stress Profiles due to interfaces (no $Sh_{min}$)

- **Case 1**
  - Top layer
  - Injection port
  - Compressive stress
  - Tensile stress

- **Case 2**
  - Top interface
  - Injection port
  - Compressive stress
  - Tensile stress
How about anisotropy?

- Single notched edge test in compression (A1)
Anisotropy and Fracture Propagation

Major contrast between Horizontal and Vertical Young’s Modulus
Anisotropy

Isotropic Case 2

Anisotropic Case 2
Stress Profiles (no Shmin) : isotropic vs. anisotropic

Stress xx (kPa)

Top layer

Compressive stress

Tensile stress

Injection port

Top interface

Compressive stress

Tensile stress

Injection port

Case 2

Dimensionless height

Dimensionless height
Fracture Mechanics vs. Damage Mechanics

• Damage mechanics model can start without initial fracture. In fracture mechanics, an initial fracture is needed.

• Connection between energy dissipated in ADaM and critical energy release rate in FM makes ADaM equivalent to FM.

• Most failure proceeds by coalescence of damage into a fracture that causes the material to become anisotropic.
Thank you

For more information, check out FracGeo’s publications