Coupled Hydro-Mechanical Simulation of Multi-Phase Fluid Flow in Fractured Shale Reservoirs using Distinct Element Method

Saeed Nazary Moghadam
PhD Candidate in Geotechnical Engineering
University of Alberta, Canada
nazarymo@ualberta.ca
Problem Statement

- **Multiphase fluid flow through porous matrix and complex deformable fracture system**
  - Matrix-matrix, matrix-fracture and fracture-fracture multi-phase fluid transfer
  - Complex fracture network
  - Pressure gradient
  - Viscous frictional force
  - Gravity
  - Interfacial tension
  - Hydro-mechanical coupling
  - Fluid compressibility and Gas solubility

![Diagram of multiphase fluid flow through porous matrix and complex deformable fracture system](imageURI)
Objective

- Developing a comprehensive coupled hydro-mechanical multi-phase fluid flow simulation approach
  - Simulating fluid flow through both porous matrix and complex deformable fractures systems in a unified grid system
  - Simulating compressible multi-phase fluid comprising of aqueous and non-aqueous liquids as well as dissolved and free gas
  - Simulating the effects of pressure gradient, viscous frictional force, gravity and interfacial tension
  - Developing an approach to hydro-mechanically couple 3-dimensional distinct element solid mechanical simulation method (3DEC) with the developed fluid flow simulation approach
  - Implementing the approach into an object-oriented C++ computational code which is flexible to be upgraded and incorporated into other codes
  - Verify the developed code and demonstrate its capabilities in evaluating the effectiveness of stimulation of fractured reservoirs by water injection
Differential form of coupled hydro-mechanical momentum conservation equation in solid phase:

\[
\frac{\partial \sigma_{ji}}{\partial x_j} + \rho b_i - \rho \ddot{r}_i - F^F = 0 \quad F^F = -\rho \dot{F} \left( \frac{\partial u_i}{\partial t} + \frac{\partial u_i}{\partial x_j} u_j \right) \quad \sigma_{ij} = \sigma_{ij}' + \alpha P \delta_{ij}
\]
Lagrangian Solid Phase Formulation
Distinct Element Method

Integral form of coupled hydro-mechanical momentum conservation equation in solid phase:

\[
\delta W = \oint_A \delta U_i \delta U_i \delta A - \int_V \sigma_{ij} \delta \varepsilon_{ij} dV + \int_V (\rho b_i - \rho \ddot{u}_i - \mathbb{F}) \delta U_i dV = 0
\]

Fracture aperture change in distinct element approach:

\[
dF_t = \begin{cases} 
K_t du_t & \text{if: } F_t < c + F_n \tan \phi \ (\text{without slide}) \\
\frac{c}{2} + dF_n \tan \phi & \text{if: } F_t \geq c + F_n \tan \phi \ (\text{with slide}) 
\end{cases}
\]

\[
dF_n = K_n du_n
\]

\[
du_n = du_t \tan \phi
\]

\[
e = e_0 + \delta u_n
\]
Eulerian Fluid Phase Formulation
Black Oil Model

Equations of motion of multi-phase fluid in porous media:

\[ u^p_i = -\frac{K k^p_r}{\mu^p} \nabla (P^p + \rho^p g z) \]

Darcy’s Law

\[ \frac{\partial}{\partial t} \left( \frac{S^w \phi}{B^w} \right) + \nabla \cdot \left( \frac{u^w}{B^w} \right) + \frac{q^w}{\rho_{Sc}^w} = 0 \]

Water Mass Conservation

\[ \frac{\partial}{\partial t} \left( \frac{S^o \phi}{B^o} \right) + \nabla \cdot \left( \frac{u^o}{B^o} \right) + \frac{q^o}{\rho_{Sc}^o} = 0 \]

Oil Mass Conservation

\[ \frac{\partial}{\partial t} \left[ \left( \frac{S^g}{B^g} + \frac{R_s^w S^w}{B^w} + \frac{R_s^o S^o}{B^o} \right) \phi \right] + \nabla \cdot \left( \frac{u^g}{B^g} + \frac{R_s^w u^w}{B^w} + \frac{R_s^o u^o}{B^o} \right) + \frac{q^g}{\rho_{Sc}^g} = 0 \]

Gas Mass Conservation

Implicit pressure-explicit saturation method

\[ (B^w - R_s^w B^g) \left[ \nabla \cdot \left( \frac{k^w}{\mu^w} \nabla P^w + CG^w - \frac{q^w}{\rho_{Sc}^w} \right) + (B^o - R_s^o B^g) \left[ \nabla \cdot \left( \frac{k^o}{\mu^o} \nabla P^o + CG^o - \frac{q^o}{\rho_{Sc}^o} \right) \right] \]

Pressure Equation

\[ \nabla \cdot \left( \frac{k^w}{\mu^w} \nabla P^w + CG^w - \frac{q^w}{\rho_{Sc}^w} \right) = \frac{\partial c_i P^i}{\partial t} \]

Water Saturation Equation

\[ \nabla \cdot \left( \frac{k^o}{\mu^o} \nabla P^o + CG^o - \frac{q^o}{\rho_{Sc}^o} \right) = \frac{\partial c_i P^i}{\partial t} \]

Oil Saturation Equation
Eulerian Fluid Phase Formulation
Finite Volume Discrete Fracture-Matrix Approach

Finite Volume Discrete Fracture Matrix Discretization

\[ \sum_{i=1}^{n_{fc}} \Lambda_{i}^{R_{i}} T_{l0l_i}^{R_{i}} \left( \frac{P_{i}^{R_{i}} - P_{l0}^{R_{i}}}{\Delta t} \right) + C_{C_{i}^{R_{i}}} + C_{d_{i}^{R_{i}}} = C_{l0}^{R_{i}} V_{l0}^{R_{i}} \left( \frac{P_{i}^{R_{i}} - P_{l0}^{R_{i}}}{\Delta t} \right) \]

Two Types of Transmissibility

\[ \alpha_{i}^{l_i} = \frac{K_{i} A_{i}}{D_{i}} (d_{i} n_{i}) \]

Matrix – Matrix
Matrix - Fracture

Fracture - Fracture
Finite Volume Black Oil Simulator (FVBOS)
C++ Implementation
Verification of FVBOS
Buckley-Leverett Problem for Porous Matrix

Agents affecting the multi-phase fluid flow:
Pressure gradient, viscous frictional force and interfacial tension between fluid phases and porous matrix

Theoretical Solution:
\[
\frac{\partial q_w}{\partial x} = -\phi A \frac{\partial S_w}{\partial t}
\]

\[
[x]_{S_w=\text{cons}} = \frac{q_t t}{\phi A} \left[ \frac{dF_w}{dS_w} \right]_{S_w=\text{cons}}
\]
Verification of FVBOS: Buckley-Leverett Problem for Single Fracture

(b) Water saturation distribution in single fracture (Aperture = 0.1 mm)

- $a = 0.1$ mm
- $h = 1$ m
- $\mu_c = 0.005$ Pa.s
- $\mu_w = 0.001$ Pa.s
- $k_w = k_w^0(\frac{1}{1 + \gamma_w a^2})$
- $\phi_w = \phi_w^0(\frac{1}{1 + \gamma_w a^2})$
- $n^w = m^w a^2$
- $s^w = e^w - 0.1$
- $k_w = k_w^0 m^w a^2 = 0.8$

(c) Water saturation distribution in single fracture (Time = 1 min)

- Aperture = 0.1175 mm
- Aperture = 0.1000 mm
- Aperture = 0.0875 mm
- Aperture = 0.0750 mm

Buckley-Leverett Theoretical Solution
Numerical Solution by FVBOS
Contribution to Current Research Projects in Reservoir Geomechanics Research Group (RG²)

- **FVBOS Involves highly complicated and uncertain physical processes**
  - Verification of FVBOS with physical models
  - Physical models generated by RG² centrifuge & 3D printing technology

- **Application of FVBOS in multi-phase fluid flow modeling**
  - Micro seismicity
  - Caprock integrity
  - Upscaling of hydro-geomechanical properties of fractured reservoir rocks
FVBOS provides
- a better tool for analyzing multiphase fluid flow in fractured reservoirs

FVBOS Provides
- a better understanding of fluid flow through naturally and hydraulically fractured reservoirs

FVBOS offers
- Hydro-mechanical coupling
- Complex deformable fracture systems
- Multi-Phase discrete fracture-matrix simulation

FVBOS is a more comprehensive alternative for
- Conventional multi-phase flow simulators
Recommendations for Future Research

- **Calibrate FVBOS based on systematic experimental Research**
  - Using 3-D printing technology of GeoPrint Facility at RG² to produce repeatable precise fractured porous samples

- **Automate FVBOS simulations by artificial intelligence and machine learning approaches**
  - Upscaling of hydro-geomechanical properties of fractured reservoir rocks
  - Train the artificially intelligent computational tool by the experimental data provided by centrifuge facility of GeoRef at RG²

- **Upgrade FVBOS by implementing stress singularity and surface energy released by fracture propagation**
  - Simulation of highly complex hydraulic fracturing processes in unconventional reservoir formations

- **Upgrade FVBOS by implementing compositional multi-phase fluid models along with a computational heat transfer method**
  - Coupled thermo-hydro-mechanical simulations in fractured unconventional reservoirs
Questions?