Reservoir Monitoring Consortium (RMC)

Semi-Annual Project Review Meeting

Early Time Analysis of Hydraulic Fracturing Using Extended Finite Element Method

Arman Khodabakhshnejad,

Los Angeles, CA
July 22, 2015
Problem Statement

- Solving fluid flow and rock deformation equations simultaneously
- Multiscale deformation near crack tip
- Tracking fluid front and fracture tip

Field Evidences:
- Warpinski (1985)

Laboratory Analysis:
- Medlin (1984)
Previous Study

Classical Model Improvement:


- Penny Shape: Abe (1976),

Numerical Models:

- Coupled Reservoir-Fracture model: Dean (2008), Hunsweck (2011),
Fluid Flow Simulation

Conservation of Mass

Darcy’s Law

\[ \nabla (\rho v) = \frac{\partial (\rho \phi)}{\partial t} \]

\[ \nabla (\rho v) + q = \frac{\partial \rho}{\partial t} \]

No Filter Cake

\{ \text{Diffusivity Equation} \}
Rock Deformation Modeling

Layered reservoir rock

- Shale as a reservoir rock
- Hard rock as a cap rock

Extended Finite Element for calculation of stress field

- Hex element
- No refinement

Transfer fluid pressure to load.

$$\sigma_{eff} = \sigma - P$$
Fracture Initiation and Propagation Model

The approach to simulate fracture:

- Cohesive segment method and phantom node.
- Traction-Separation law.
- Crack jumps from one element face to another.

Tvergaard, 1992

Song, et al, 2005
Fracture Initiation and Propagation RMC Model

- Failure initiation criteria: Maximum Principal Stress

\[ f = \left\{ \frac{\langle \sigma_{\text{max}} \rangle}{\sigma_{\text{max}}} \right\} \]

No Damage if \( \sigma_{\text{max}}^0 > \sigma_{\text{max}} \) & Separation < \( D^0 \)

- Fracture evolution: Displacement

![Graph showing the relationship between Traction, Maximum allowable Traction, Linear Elastic Behavior, Degradation, Maximum Displacement, and Separation.](image)
Coupled Hydraulic Fracturing Simulation Algorithm

Start

Initialization

Calculate Rock Deformation

Calculate Fluid Pressure

Max |w_{f}^{n+1} - w_{f}^{n}| < \epsilon

Increase Time

Fracture propagation criteria is satisfied?

Yes

Finish

No

Time Step is Adjusted Automatically

Iteration Loop

\{ Building Rock Model Preliminary Rock Model \}

\{ Initializing Fluid Properties \}

\{ Time Length Leak – off Rate \}
Case 1: Constant Pressure - Non Viscous Fluid - No Initial Dry Zone.

Case 2: Constant Injection - Viscous Fluid - Small Initial Dry Zone.

Case 3: Constant Injection - Compressible Fluid - Large Initial Dry Zone.
Results

<table>
<thead>
<tr>
<th>Shale Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus (Gpa)</td>
</tr>
<tr>
<td>Poisson’s Ratio (fraction)</td>
</tr>
<tr>
<td>Permeability (mD)</td>
</tr>
<tr>
<td>Porosity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cap Rock Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus (Gpa)</td>
</tr>
<tr>
<td>Poisson’s Ratio (fraction)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Geometrical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix Dimension (m³)</td>
</tr>
<tr>
<td>Fracture Radius (m)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fluid Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Rate (m³/sec)</td>
</tr>
<tr>
<td>Viscosity (cp)</td>
</tr>
</tbody>
</table>

Analytical Solution of Griffith-Sneddon
Constant Pressure-No Dry Zone

\[ V = \frac{16(1 - \nu^2)r^3(p - \sigma)}{3E} \]
Case 1: Constant Pressure - Non Viscous Fluid - No Initial Dry Zone

Effect of Initial Fracture Size

- \( r = 1 \text{ m} \)
- \( r = 2 \text{ m} \)
- \( r = 6 \text{ m} \)
- \( r = 10 \text{ m} \)

Volume, \( m^3 \) vs. Pressure, \( \text{pa} \)

Sneddon Solution
Numerical Simulation
Case 1: Constant Pressure - Non Viscous Fluid - No Initial Dry Zone

Effect of Fluid Pressure

- **P = 1 pa**
  - Sneddon Solution
  - Numerical Model

- **P = 10 pa**
  - Sneddon Solution
  - Numerical Model

- **P = 100 pa**
  - Sneddon Solution
  - Numerical Simulation

- **P = 1000 pa**
  - Sneddon Solution
  - Numerical Simulation
Case 2: Constant Injection - Compressible Fluid - Small Initial Dry Zone
Case 2: Constant Injection - Compressible Fluid - Small Initial Dry Zone
Case 3: Constant Injection - Compressible Fluid - Large Initial Dry Zone
Case 3: Constant Injection - Compressible Fluid – Large Initial Dry Zone
Effect of Dry Zone

Volume, m^3

Time, S
Conclusion

- Numerical model matches the analytical solutions in corresponding boundary conditions.

- Effect of dry zone is quantified for different rock/fluid configurations.

- Rate of fluid volume growth is greater than rate of fracture volume growth. It implies that the dry zone gradually diminishes over the time.
Future Work

- The algorithm will be tested for transient and late time analysis of hydraulic fracturing.

- Leak-off term will be modified to incorporate effect of mud cake on the fracture walls.

- A realistic model of reservoir will be created for modeling fracture propagation in presence of a natural fracture network.
Thank You

Questions?

rmc.usc.edu