Modeling Microseismicity Using Damage Mechanics: An Example from Hydraulic Fracturing Case

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Based on Papers:
Guest, A. and Settari, A., 2010. SPE 137936,
Complex problem to model

- Reservoir modeling – fluid motion in porous medium
- Geomechanical modeling – response of rock to fluid motion
- Fracture mechanics – where fractures originate and how they propagate
- Earthquake seismology – record of fracturing in-situ
- Rock mechanics – fracturing under controlled conditions
- Geology – pre-existing fractures, heterogeneities
Damage Mechanics
In tensional regime:

\[
\sigma = \frac{F}{S} = \varepsilon E
\]

\[
\varepsilon = \frac{F}{SE}
\]

\[
\varepsilon_1 = \frac{F}{S_1 E} = \frac{F}{SE_D}
\]

\[
D = 1 - E_D / E
\]

In compressional regime: the fracture still carries a part of the load

\[D_C = 0.2D\]

(Lemaitre and Desmorat, 2005)
Geomechanical Equations

- Equilibrium equations:
  \[ \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i = 0 \]

- Constitutive equations – linear elasticity:
  \[ \tau_{ij} = \frac{E \sigma}{(1+\sigma)(1-2\sigma)} \varepsilon_{kk} \delta_{ij} + \frac{E}{1+\sigma} \varepsilon_{ij} + \alpha p \delta_{ij} \]

- Mohr–Coulomb criterion for shear:
  \[ \sigma_1 - \frac{1 + \sin \phi}{1 - \sin \phi} \sigma_3 > f_{c0} \]
Reservoir characteristics

- Heterogeneity of rock strength and Young’s modulus arising from natural fracture distribution
- Statistics of extreme failure is controlled by the weakest link
- Weibull distribution with the probability density function:

\[
f (\sigma) = \frac{m}{\sigma_0} \left( \frac{\sigma}{\sigma_0} \right)^{m-1} \exp \left[ - \left( \frac{\sigma}{\sigma_0} \right)^m \right]
\]
Example of Damage Mechanics

- **Constant strain rate**
  - **Tension**
  - Final strain: 0.0007
  - $m=3$
  - Numerically simulated damage

- **Constant strain rate**
  - **Compression**
  - Final strain: 0.002
  - Fixed
  - Numerically simulated damage
Effective Young’s Moduli based on Joints Mechanics

Effective moduli $E_D$ in the jointed medium (Bagheri and Settari, 2006):

$$\frac{1}{E_D} = \frac{\cos^4 \alpha}{Sk_n} + \frac{1}{E}$$

<table>
<thead>
<tr>
<th>Spacing [m]</th>
<th>Stiffness [MPa/ m]</th>
<th>$E$ [GPa]</th>
<th>$E_D$ [GPa]</th>
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<tbody>
<tr>
<td>0.1</td>
<td>1.00E+03</td>
<td>41</td>
<td>0.10</td>
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</tr>
</tbody>
</table>

S - joint spacing
Kn - joint normal stiffness
$\alpha$ - dip angle
$E$ - matrix modulus
$E_D$ - equivalent modulus

Stiffness of joints: Bandis et al., 1983
1. Unloading of pre-existing joints and fractures due to the low effective stress

\[ K = k_0 e^{\beta(\alpha_p)} \]

2. Fracturing occurring during the stimulation

\[ K_{ij}^F = \eta \frac{W_{fe}^3}{12S} (\delta_{ij} - n_i n_j) \]
Fluid flow and geomechanical response are fully coupled through pressure and permeability.

Fluid model – commercial package Geosim, has a capability to include propagation of a hydraulic fracture and stress– or pressure–dependent permeability tensor.

Geomechanical MS model added as a module – solves equilibrium equation and constitutive equation (linear elasticity with poroelasticity).

Formation of fractures: according to Mohr–Coulomb criterion, conjugate system of faults.

Fracture modeling: using damage mechanics (damage to Young’s modulus).

Software for MS model: Finite difference code in Fortran, post-processing in Python.
Bossier Tight gas Example
Set up: Important to Capture Right Scale

- **Main Fracture**: propagation independently through another modulus, deformation through damage mechanics modulus

- **Mesofractures**: size of the representative volume; form process zone around the main fracture; we assume that they correspond to MS events

- **Microfractures**: their effect averaged in the Representative Volume Element (REV); their coalescence is represented through Mohr–Coulomb limit; the variability is described using heterogeneity
Example of coupling – Flow model of Bossier

- Fracturing in a tight sandstone, 0.01 md, in Texas
- Vertical fracture, ~2 hour injection

Local heterogeneities estimated from MS, bipolar distribution
Example of coupling – Flow model of Bossier

Uncoupled solution from: (Ji and Settari, 2009)

Fit is ensured by assuming a pressure-dependent leak-off into the reservoir
• Good match to about distance of 60 ft, the more distant MS is probably a location error.
Permeability changes with time

- \( k_{11}, \text{[mD]} \)
- Time: 53 minutes
- Time: 104 minutes
- Time: 165 minutes

Distance, ft

Log10

Log10
Overestimated Permeability
Stochastic Reservoir Heterogeneity

- Different reservoir heterogeneity will give different MS distribution

The three cases differ in that: a) has a fine grid in x direction, b) is like a) but with enhanced permeability, c) has heterogeneity distribution with m=3.
Summary of Results

- The coupled modeling shows that new fracturing in the reservoir has an important effect on fluid leak–off and main fracture propagation, but the effect is dependent on the pre–existing heterogeneities of the reservoir.

- We conclude that the permeability enhancement and the increased leak–off determined from the microseismic distribution alone is not sufficient to characterize the total leak–off into the formation. As a result, the total permeability enhancement of the stimulated reservoir volume (SRV) appears to include both the scale of the microseismic events and all the scales that are smaller.

- Even though the shear events develop first, the permeability of such fractures is not high enough to take away all fluid. Therefore the permeability of the main fracture remains the main driving mechanism during the stimulation phase in the studied case and most likely in other similar cases where main hydraulic fracture develops.
Conclusions

- Damage mechanics is a very efficient method
- The hard part of modeling is in the proper description of the reservoir.
Questions?
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