Discrete Element Modeling of Fractured Reservoirs

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Introduction

• Extraction of the abundant reserves of shale gas in North America and elsewhere in the world has become economical because of advances in horizontal drilling and hydraulic fracturing.

• Success of engineered geothermal systems (EGS) critically depends on stimulation of rock mass typically done with fluid injection.

• However, hydraulic treatment of fractured rock reservoirs is still more of an art than engineering or science.
Main Challenges

• Complexity of the multiple, coupled processes
• Complexity of geology, particularly regarding natural fracturing
• Inaccessibility of treated rock formations
Conventional Analytical Tools

• Conventional software for simulation of hydraulic fracturing are based on a number of simplifying assumptions
  – the rock mass is a homogeneous continuum;
  – the fracture surface is planar;
  – the fracture develops as two wings that propagate symmetrically relative to the wellbore.

• There is a need for improved analytical tools that can be used for more effective design of rock mass treatment by fluid injection

• The issue important for number of industries
Synthetic Rock Mass?

- Rock typically contains many *natural* discontinuities, such as faults, bedding planes, cracks, fractures and joints.

- Appear at many scales.

- Often **dominate the behavior** because they are weaker than the intact fabric...
  - sliding, opening, fluid conduction etc.

- Often **not continuous**
  - failure involves fracture of intact rock.

- Need to predict *(model)* the behavior of a **rock mass**
  - collective of joints and intact rock with failure on both and full interaction between them.

After Pariseau (2009)
Role of Heterogeneities and Discontinuities

- Faults
- Joints
- Layers
- Interbedding
- Anisotropy
- Lenses
- Veins

Distinct Element Method (DEM) Codes

• Rock mass represented as an assembly of polygonal or polyhedral blocks
• Contacts between blocks represent joints in the rock mass
• Representation of partially fractured blocks and progressive fracture propagation
• Fractures limited to predefined contacts
Representation of DFN

Cut 1

Cut 2

Cut 3

Block after cutting
To account for fractures of finite extent, different material properties are set to subcontacts inside and outside of fractures.

All fractures need to be pre-defined, including the HF plane.
Hydro-Mechanical Coupling

• Flow in joints approximated using lubrication equation
• Fully coupled hydro-mechanical analyses
  – Effect of joint deformation on aperture (permeability)
  – Fluid pressure effect on deformation and strength of joints
  – Effect of joint deformation on fluid pressure changes
Conceptual Model

**FULLY CONNECTED DFN**

- Diffusion without slip
- Increase in dimensionless injection rate, $\bar{q}$
- Fracture opening due to pressure increases and sliding
- Fracture opening due to pressure increases

Decrease in stress ratio $k$

\[ \Delta p \propto \bar{q} \]

\[ \bar{q} = \frac{q \mu}{\kappa \gamma Hr} \]
Dilation in DEM

DEM model consists of an assembly of intact rock blocks separated by joints/fractures.

Fractures are represented by smooth surfaces.

Condition for slip: \( \tau = (\sigma_n - P) \tan \varphi \)

Once pressure reaches a critical value slip occurs.

When subjected to shear displacements, surface roughness results in some permanent opening normal to the fracture surface.

\[ \Delta d_n = \Delta d_s \tan \varphi_{\text{dil}} \]
Effect of Fracture Length Distribution

- Three different realization with different length characteristics are considered

Aperture change due to stimulation
THM Simulations: Effect of Fracture Length Distribution

- 34 months of production

Rock temperature

Realization I

Realization II

Realization III

Fluid temperature
New Methodology

- Over the past few years, Itasca has been developing and applying the Synthetic Rock Mass (SRM), which was based on the code PFC2D/3D.
- PFC2D/3D is a distinct element code (DEM) that models a elastic/brittle rock as a bonded assembly of spherical particles, so called bonded particle model (BPM).
- The joints of the SRM are represented by a special contact model (the smooth joint model, or SJM) that respects the sliding planes, independently of the local contact normals.
Synthetic Rock Mass

Intact rock representation by DEM (including brittle fracture)

Bonded-particle assembly intersected with fractures (using the Smooth Joint Model – SJM)

Fracture representation – 3D DFN (Discrete Fracture Network)
BPM of Brittle Rocks - Damage
Smooth Joint Model (SJM)

Where joint (discontinuity) planes cut springs, the angle of the plane is respected (not the spring orientation). Thus, shear and normal compliances for the joint are used instead.

In addition, slip and opening/closing of joint elements are modeled. Sliding on joint planes is independent of the local orientations of component springs.
Advantages of SRM

• Mechanics based approach
• Represents the dominant mechanisms
• Standard testing methods can be used to provide necessary input parameters for both model components
Fracture Flow

• Fluid flow and storage are based on a network of reservoirs (fluid elements) and pipes
• The fluid elements coincide with the contacts cut by joint planes, and by contacts that break (new microcracks)
• The fluid network is updated continuously as new fracturing occurs
HF Simulation Using PFC2D

PFC2D 4.00
Step 61569 08:25:53 Fri Mar 13 2009

View Size:
X: -1.250e+001 <= 1.250e+001
Y: -1.383e+001 <= 1.383e+001

FISH function pressure_item
FISH function sj_pi_geom
FISH function crk_item
FISH function pressure_item
FISH function sj_pi_geom
FISH function crk_item

Displacement
Maximum = 1.400e-005
Scale to Max = 5.000e-003
Linestyle
What is Lattice

• The Lattice is a quasi-random array of nodes and springs in 3D

• For a given resolution (mean node spacing) spring stiffnesses are adjusted such that the ensemble modulus (and Poisson’s ratio) matches that of the target rock.
• Springs may break (microcracks), and their strength is adjusted to give the correct rock strength.
Lattice

• The new 3D code, *HF Simulator*, is based on lattice, a simplified form of the DEM
• Balls are replaced by point masses and contacts are replaced by springs
• Great increase in efficiency – for example a 10-million particle model can be created and run on a laptop PC
• Small strain assumption
Simple Example Problems

(a)  
Sketch Model
- Origin
- Joints
- Boreholes
- Clusters
- Rock

(b)  
Joint 1
Joint 2
Joint 3
Continuum Homogeneous Medium
Fractured Medium
Synthetic Microseismicity
Tensile Events
Slip Events
Fracture Interaction

a) one cluster

b) two clusters

c) three clusters
d) five clusters
Step Toward Fracture Network Engineering

Synthetic microseismicity from a generic 3D model

Example observed seismicity

Interpreting fracture diagnostics from microseismic data provides a double feedback for engineering the network.
Science and Engineering Challenges

- **Understanding...**
  - Better understand the role of critical DFN characteristics on interaction with hydraulic fracture

- **Design...**
  - Develop work flows and methodologies leading to practices for optimizing the stimulation
  - Well-specific design considering field data and understanding of rock mechanics

- **Implementation...**
  - Field monitoring and feedback loop to full-scale models, with realistic field complexity, so as to “control” the stimulation