Three-dimensional Modeling of Fracture Clusters in Geothermal Reservoirs

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EGS Component R&D › Stimulation Prediction Models

May 18, 2010

Bons (2000)
Overview

- **Timeline**
  - Project Established: October, 2009
  - Project End: December, 2011
  - Percent Completed: 25-30%

- **Budget**
  - Total project funding: $1,017,984
  - DOE share: $685,141
  - Awardee share: $171,285
  - Funding received in FY 09: $275K, funding for FY10: $685K

- **Barriers**: Site/Well Characterization: Accurate Prediction of Reservoir’s Response to Stimulation

- **Partners**: AltaRock Energy, Inc., Sandia National Laboratory
Relevance/Impact of Research

• The objective of this is to develop a 3-D numerical model for simulating mode I, II, and III (tensile, shear, and tearing) propagation of multiple fractures using the virtual multi-dimensional internal bond (VMIB), to predict geothermal reservoir stimulation

• First year targets:
  – Elaborate the three-dimensional multiple internal bond method; study WARP3D for consideration of implementing VMIB
  – implement VMIB in 3D FEM and compare model with lab results, conduct verification simulations and add hydraulic fracture routines
Relevance/Impact of Research

• By helping remove barriers to reservoir design, the project will help increase reserves and lower costs

• Permeable zones have to be created by stimulation, a process that involves fracture initiation and propagation in the presence of natural fractures

• Fracture propagation is a 3D problem and can be driven by hydraulic pressure and thermal stress, etc.

• Fracture can propagate in modes other than tensile
  – Reservoir creation and control
Scientific/Technical Approach

• Physical processes considered
  • Fully-coupled poro-thermoelastic constitutive equations
  • Non-linear rock deformation
  • Rock heterogeneity
  • Modes I, II, III
    – Pressurization and cooling
    – Pore pressure effects
    – Fracture interactions

• Calibration using lab and field data such as stress-strain behavior and pressure-time record
Scientific/Technical Approach

• Poro-thermoelastic Constitutive Equations

\[
\dot{\sigma}_{ij} = 2G \dot{\varepsilon}_{ij} + \left( K - \frac{2G}{3} \right) \dot{\varepsilon}_{kk} \delta_{ij} + \alpha \dot{p} \delta_{ij} + \gamma_1 \dot{T} \delta_{ij}
\]

\[
\dot{\zeta} = -\alpha \dot{\varepsilon}_{ii} + \beta \dot{p} - \gamma_2 \dot{T}
\]

• Virtual Internal Bond (VIB)

- Material consists of particles interacting (in the micro scale) through a network of virtual internal bonds (Kline, Gao, 98)

- The macro constitutive relation is derived directly from the cohesive law between material particles.

\[
\gamma_1 = K \alpha_m, \quad \beta = \frac{\alpha - \varphi}{K_s} + \frac{\varphi}{K_f}
\]

\[
\gamma_2 = \alpha \alpha_m + (\alpha_f - \alpha_m) \phi
\]
Scientific/Technical Approach

• Virtual Multiple Internal Bond (VIB)

Fracture criterion is implicitly incorporated into the constitutive relation by cohesive law. It is not necessary to employ a separate fracture criterion.

Shear effect is considered in the interaction of material particles.

By developing a suitable bond evolution function, the VMIB can successfully simulate fracture initiation and propagation.

\[
\Phi = \int_0^{2\pi} \int_0^{2\pi} U_L D(\theta, \phi) \sin(\theta) d\theta d\phi + \int_0^{2\pi} \int_0^{2\pi} \left( U_{R1} + U_{R2} + U_{R3} \right) D(\theta, \phi) \sin(\theta) d\theta d\phi
\]

Contributed by Normal stiffness

Contributed by Shear stiffness
Significance & Impact of Research

• Model 3D fracture propagation in multiple modes
  • Consider rock heterogeneity
  • 3D stress state
  • Fracture-natural fracture interaction
  • Pore pressure and thermal stress
  • Multiple cracks
  • Needs no re-meshing
  • No explicit fracture criterion
Scientific/Technical Approach

• Phase 1: Model development
  
  – Elaborate the three-dimensional multiple internal bond method
  – Implement VMIB in 3D FEM and compare model with lab results, conduct verification simulations and add hydraulic fracture routines.
  – Implement in a 3D FEM; also use FEAP3D
**Scientific/Technical Approach**

- **Future work**
  - Continue to develop the 3-D VMIB numerical model for propagation of multiple fractures in mixed mode (tensile, shear, and tearing) to aid in geothermal reservoir stimulation design.
  - Continue with code development and consider combined poro-thermoelastic effects in 3D multiple fracture propagation.
  - Develop special algorithms to improve accuracy and to enable fracture-natural fracture interaction in 3D.
3D finite element model with VMIB has been developed

– Preliminary results show good agreement with lab data
– VMIB has been combined with pore pressure & poroelastic stress
– Routines for fracture-natural fracture coalescence has been developed
– Rock heterogeneity can be considered
Accomplishments, Expected Outcomes and Progress

Simulation of Fracture Propagation

1) **Mixed mode (I-II) crack test problem:**
Young’s modulus E=38.4 GPa,
Poisson ratio = 0.12, Tensile strength= 3.2 MPa.

Comparison between simulated and experimentally measured P-CMOD crack mouth opening displacement.
2) Mixed mode (I-III) test problem:

Planar crack embedded in rock subjected to compressive stress with same properties as before

The fracture process simultaneously involves mode I and III which cannot be simulated by a 2D model.

Partition modes of tetrahedron element: (a) type I: triangular fracture area; (b) type II: quadrangular fracture area
Embedded Fracture in Compression

Propagation is in tensile mode at the “tips”, but then proceeds in the lateral direction in tearing mode due to the relative slip between fracture faces.
3) Test problem for poroelastic VMIB:

Compression of a poroelastic column of rock and calculation of the ensuing displacements and pore pressure.

Comparison of the numerical and analytical results for displacement of the top surface is shown. The numerical results are in good agreement with the analytical solution.
4) Rock Failure in uniaxial compression

Failure simulation using the poroelastic VMIB has a form similar to those in other works with similar failure plane orientation.
- Work will continue on schedule
- Bulk of work done by graduate students, Post-Doc
- Will explore attracting funds from petroleum industry-Crisman Institute
- This project integrated with other projects through workshops; demonstration projects
- Exchange of ideas during visit by scientist from Sandia
Future Directions

- The goal is to have a 3D fracture model to help predict reservoir stimulation
- The model will be applied to interpretation hydraulic fracture experiment published and planned by AltaRock

Future work includes
- Continue to develop the 3-D VMIB numerical model for propagation of multiple fractures in mixed mode (tensile, shear, and tearing)
- Code development to consider combined poro-thermoelastic effects and multiple fracture propagation in 3D.
- We will develop special algorithms to improve accuracy and to enable fracture-natural fracture interaction in 3D
- Comparison with laboratory compression tests
• We have developed the VMIB method for 3D fracture propagation in rock
• Numerical algorithms have been developed to allow element partitioning, application of hydraulic pressure, and consideration of heterogeneity
• A 3D elastic fracture propagation model has been developed and verified against experimental results. The model has successfully predicted mode I and mode III fracture growth in compression
• A 2D poroelastic VMIB model has been fully developed first and applied to show the potential of the approach
Related Publications


Hydraulic fracturing in heterogeneous rock; $\sigma_x=1\text{MPa}$, $\sigma_y=0.5\text{MPa}$ effective stress (a) and pore pressure (b) distribution at time 25s.

Multiple hydraulic fracturing; $\sigma_x=1\text{MPa}$, $\sigma_y=0.5\text{MPa}$; effective stress (a) and pore pressure (b) distribution at time 30s.
Simulated specimen for compressive fracture, Shen et al., 1995.

\[ L = 12.7 \quad \alpha = 45^\circ \quad \beta = 45^\circ \]

(a) deformed mesh configuration ; (b) details of the middle part. 
(b) (displacements are magnified 100 times).