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Three-dimensional Modeling of Fracture Clusters in Geothermal Reservoirs

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EGS Component R&D › Stimulation Prediction Models

Relevance/Impact of Research

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- The objective is to develop a 3-D numerical model propagation of multiple fractures to help predict geothermal reservoir stimulation using VMIB
- Able to simulating mode I, II, and III (tensile, shear, and tearing)
- Consider thermal and poroelastic effects; alleviate the need for explicit propagation criterion
- Help remove barriers to reservoir design, the project will help increase reserves and lower costs
  - Contribute to securing the future with Enhanced Geothermal Systems
  - Permeable zones have to be created by stimulation, a process that involves fracture initiation and propagation in the presence of natural fractures
  - Fracture can propagate in modes other than tensile
  - Reservoir creation and control

- Physical processes considered
  - 3D fracture propagation driven by hydraulic pressure and thermal stress
    - Pressurization and cooling
    - Pore pressure effects
    - Fracture interactions
  - Non-linear rock deformation
  - Rock heterogeneity
  - Modes I, II, III
- Calibration using lab and field data such as stress-strain behavior and pressure-time record

- Thermo-poroelastic Constitutive Equations

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

$$\gamma_1 = K\alpha_m \qquad \beta = \frac{\alpha - \varphi}{K_s} + \frac{\varphi}{K_f}$$

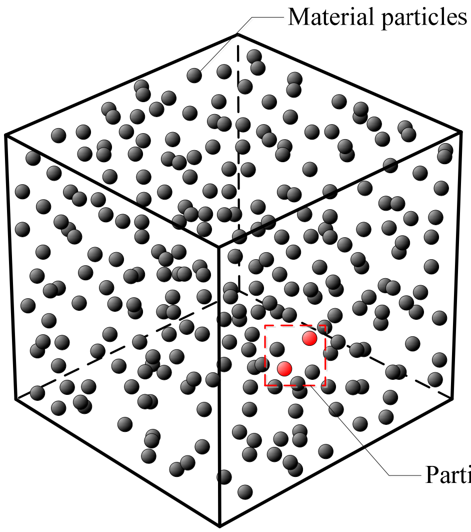
$$\dot{\zeta} = -\alpha\dot{\varepsilon}_{ii} + \beta\,\dot{p} - \gamma_2\dot{T}$$

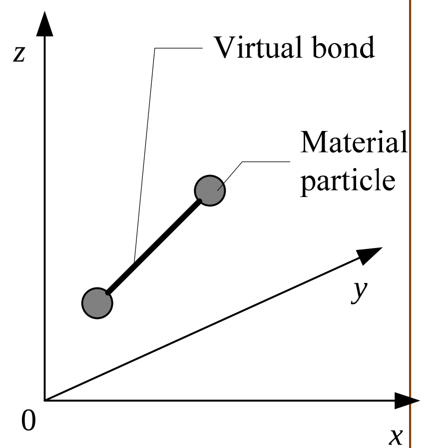
$$\gamma_2 = \alpha\,\alpha_m + \left(\alpha_f - \alpha_m\right)\phi$$

- Virtual Internal Bond (VIB)

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

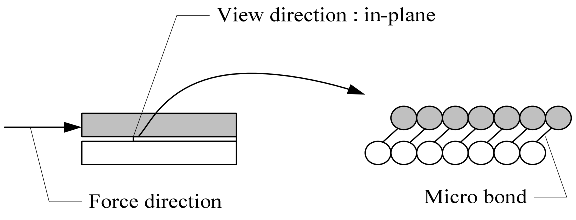
-The macro constitutive relation is derived directly from the cohesive law between material particles



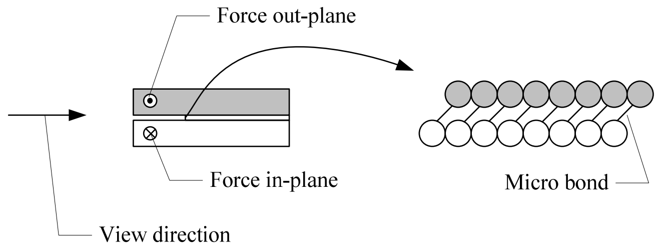


- Virtual Multiple Internal Bond (VIB)

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 functions, the VMIB successfully simulates fracture initiation and propagation.

Bond density function

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

Contributed by Normal stiffness — Contributed by Shear stiffness

Scientific/Technical Approach

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- Model 3D fracture propagation in multiple modes
  - Consider rock heterogeneity; 3D stress state; pore pressure and thermal stress
  - Multiple cracks, no explicit fracture criterion
  - Mixed mode (tensile, shear, and tearing) to aid in geothermal reservoir stimulation design
  - Develop special algorithms to improve accuracy and to enable fracture-natural fracture interaction in 3D
  - Compare with experiments, field data

Accomplishments, Results and Progress
Natural Fracture propagation in Mixed-Mode

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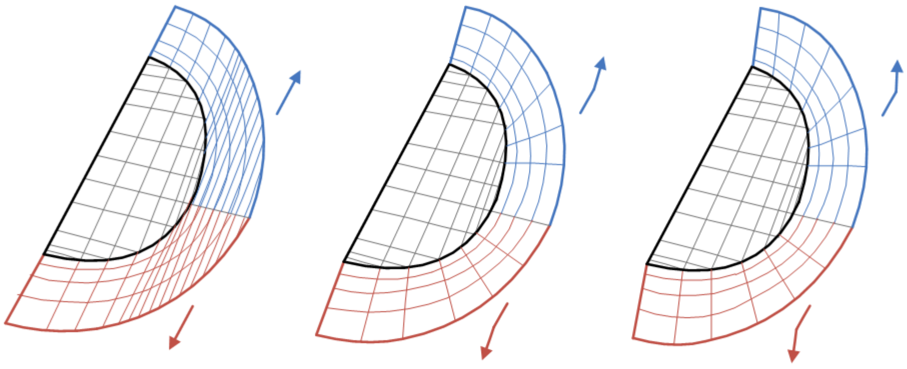
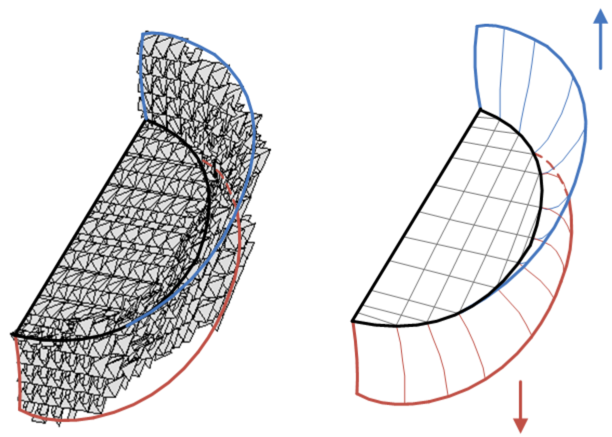
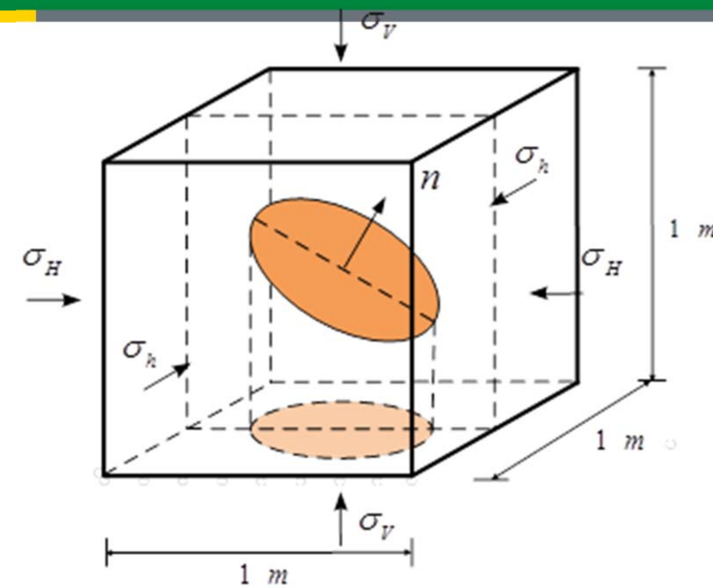
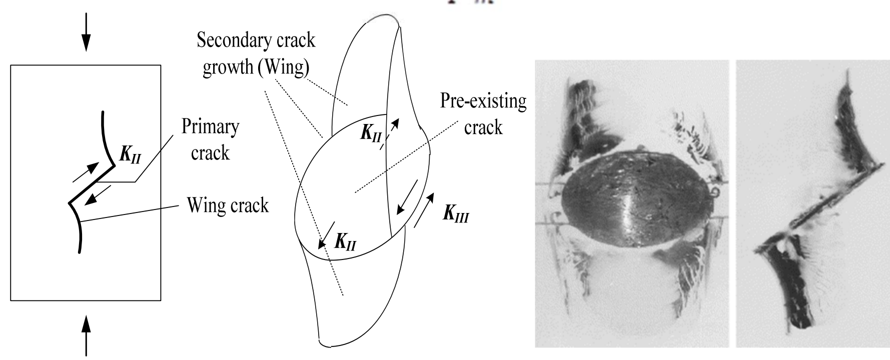


(a) (b) (c)



(d) (e)





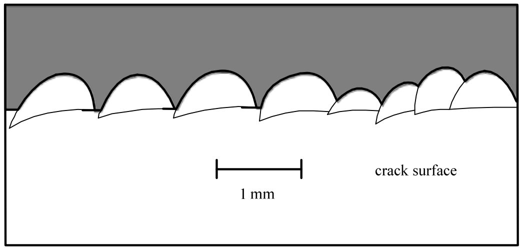
Case I: $\sigma_V = 0.8, \sigma_h = 0.8, \sigma_H = 0.8, \; p_0 = 1.6\,\text{MPa}$

Case II: $\sigma_V = 1.6, \sigma_h = 0.8, \sigma_H = 0.8, \; p_0 = 2.4\,\text{MPa}$

Case III: $\sigma_V = 2.0, \sigma_h = 0.8, \sigma_H = 0.8, \; p_0 = 2.8\,\text{MPa}$

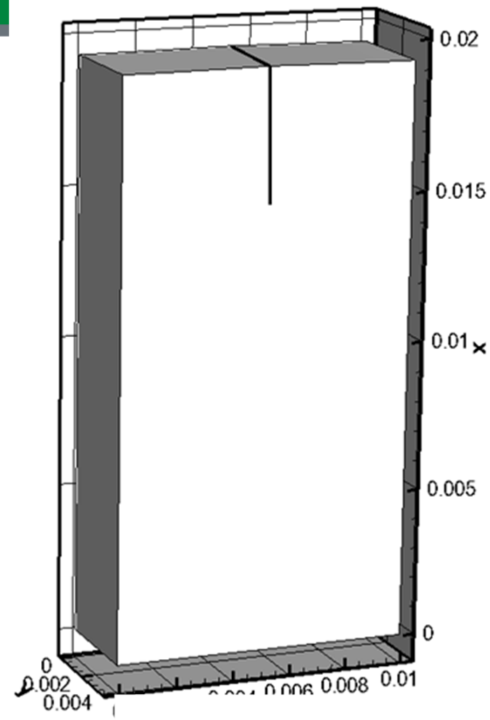
Case IV: $\sigma_V = 2.4, \sigma_h = 0.8, \sigma_H = 0.8, \; p_0 = 3.2\,\text{MPa}$

Fragment of a resin sample with a single wing crack. (two horizontal lines are threads holding the inclusion) from experimental results of Dyskin et al (2003). Two-D wing crack growth (**K**$_{II}$) and 3D wing crack growth (Mixed mode of **K**$_{II}$ &**K**$_{III}$).

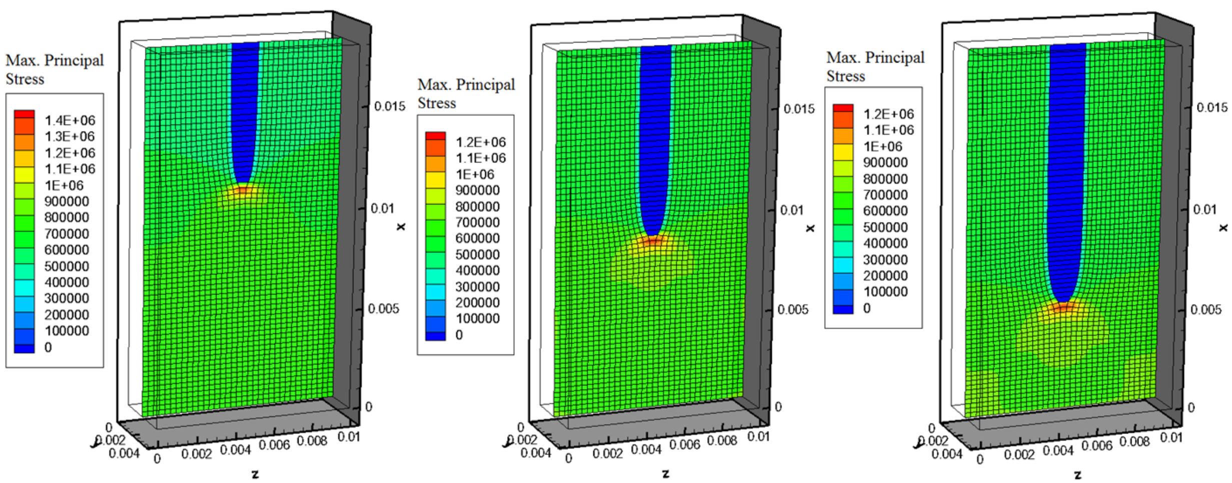


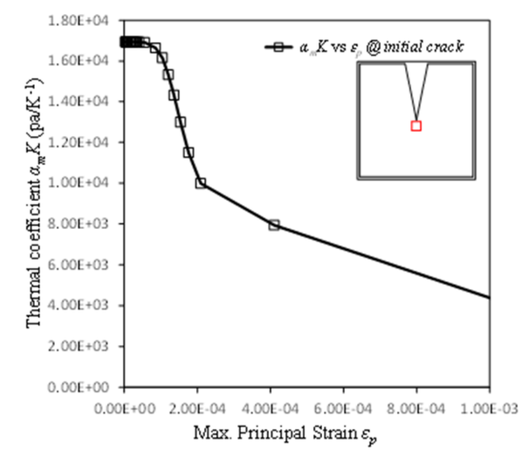
3D VMIB Model for Thermal fracturing

A cubic of granitic rock having a fracture as shown is simulated. Uniform cooling is assumed to test the mechanical response. The normal displacement of all rock surfaces except the top one are confined.



The middle slice of maximum principal stress contour with deformed mesh configuration (amplified 1200 times) when the rock is cooled by: (a)-3 ;(b)-6 ;(c)-9 ;(d)-12 ;(e)-15 ;(f)-18 .





3D VMIB Model for Thermal fracturing

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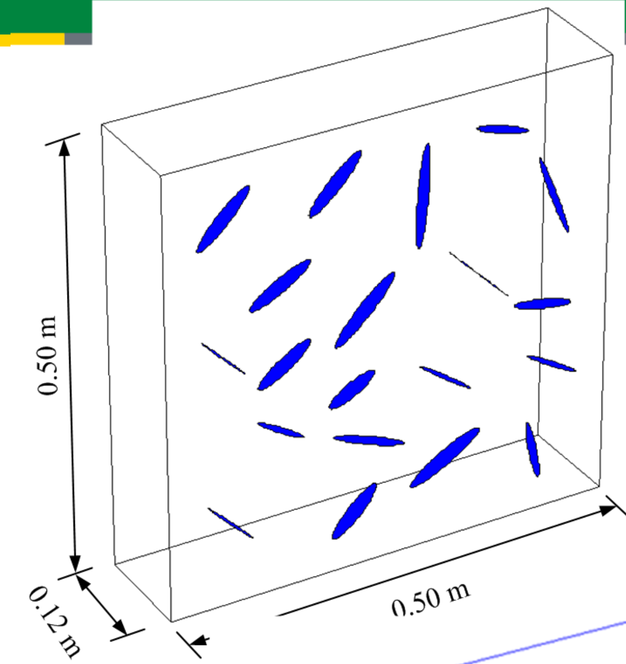
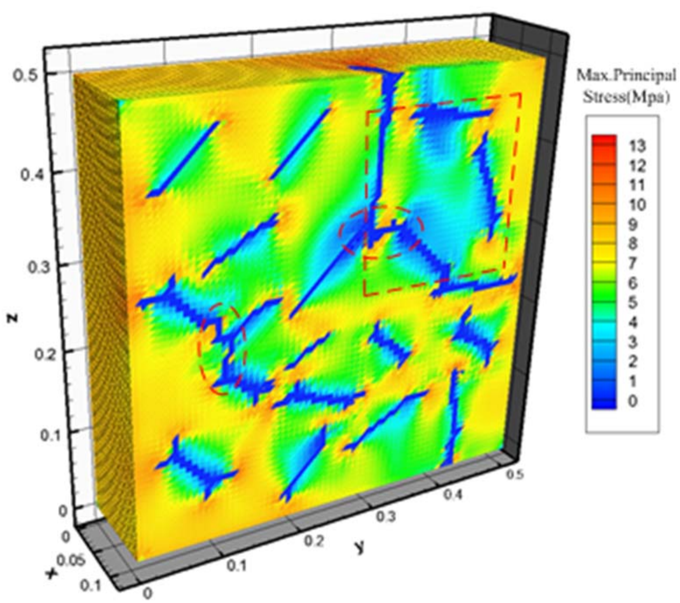
Randomly Distributed Multiple Fractures

Thermal fracture propagation and interaction. Multiple fractures are simulated with a structured mesh without re-meshing

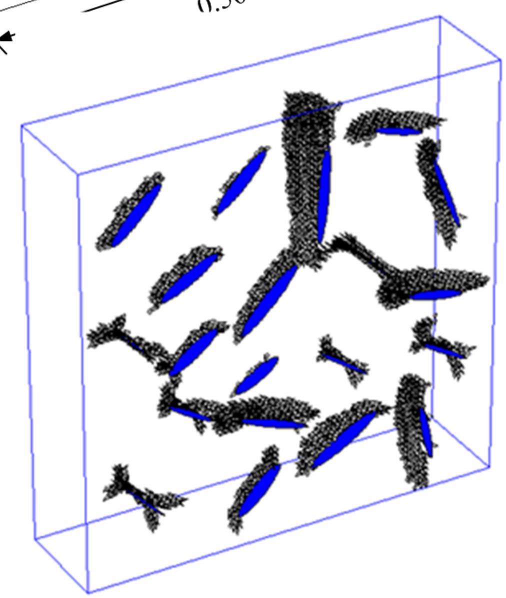
A cubic specimen of granitic rock with 20 randomly distributed small fractures is considered





Left: maximum principal stress contour when the rock was cooled by:-38 C.

Right: Propagation of thermal fracture when the rock was cooled by: -38 C.



3D VMIB Model for Thermal fracturing

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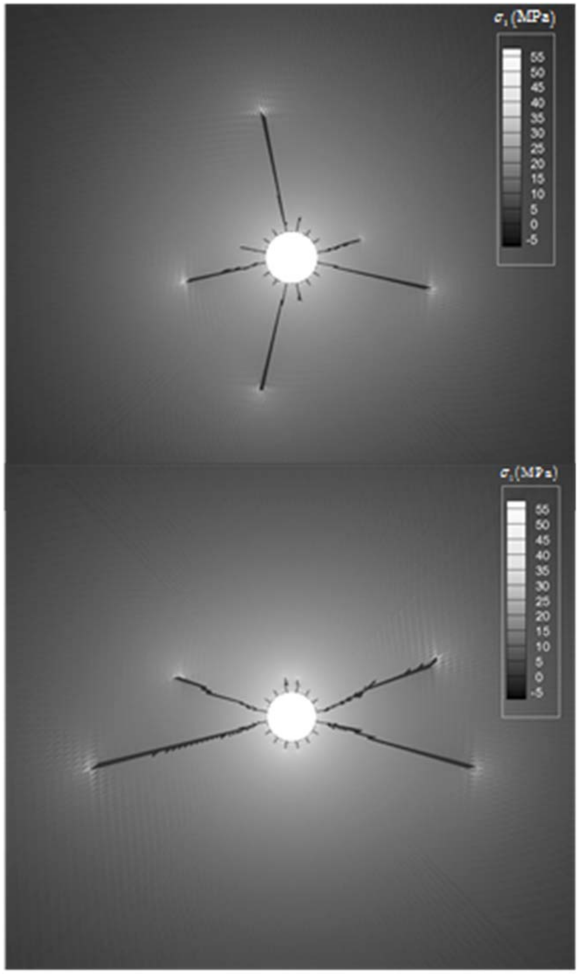
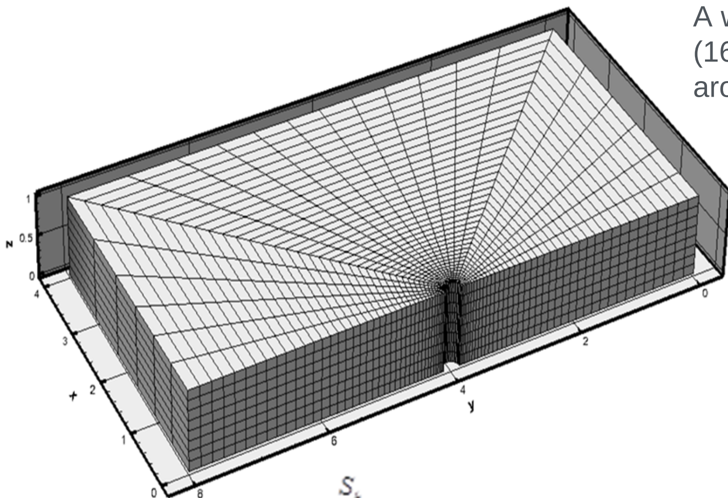
Randomly Distributed Multiple Fractures:

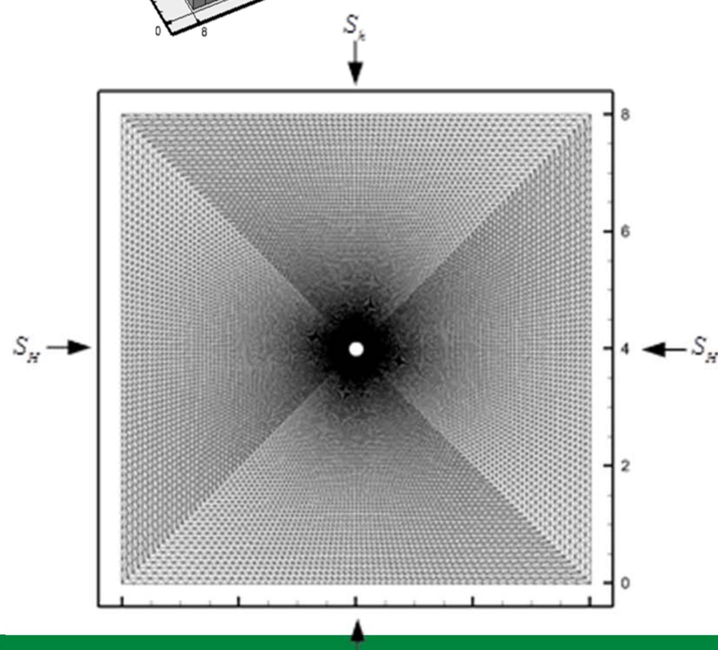
Left (top) isotropic stress state; (bottom) anisotropic stress

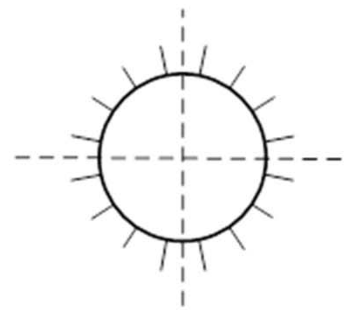




A wellbore with multiple pre-existing cracks (16) of 3.33-4 cm long are equally spaced around the well

The initial temperature in the matrix is 200 C and 40 C on the surface of wellbore





Poroelastic VMIB Model

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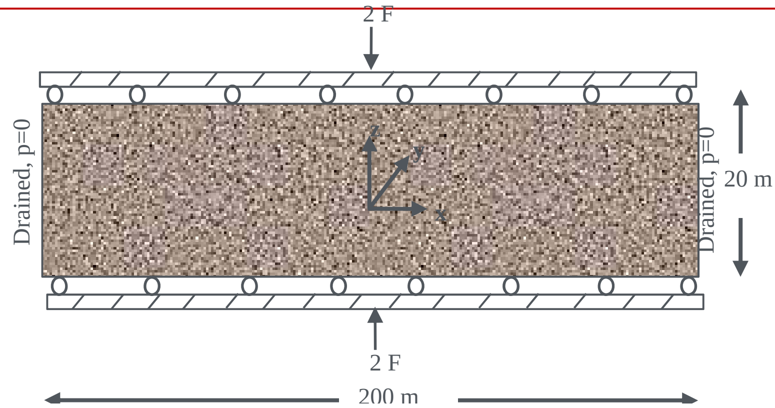
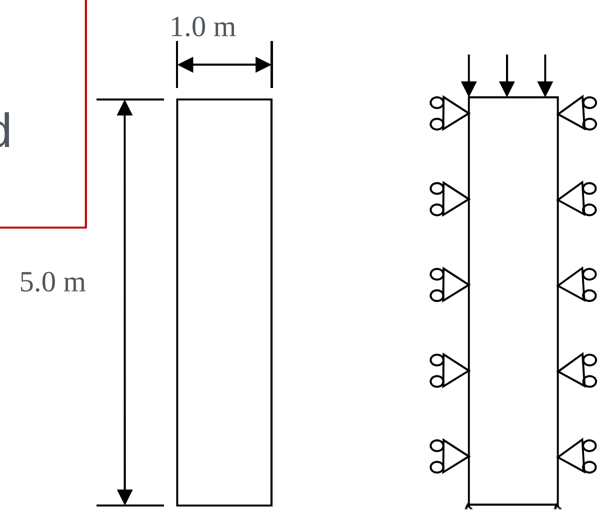
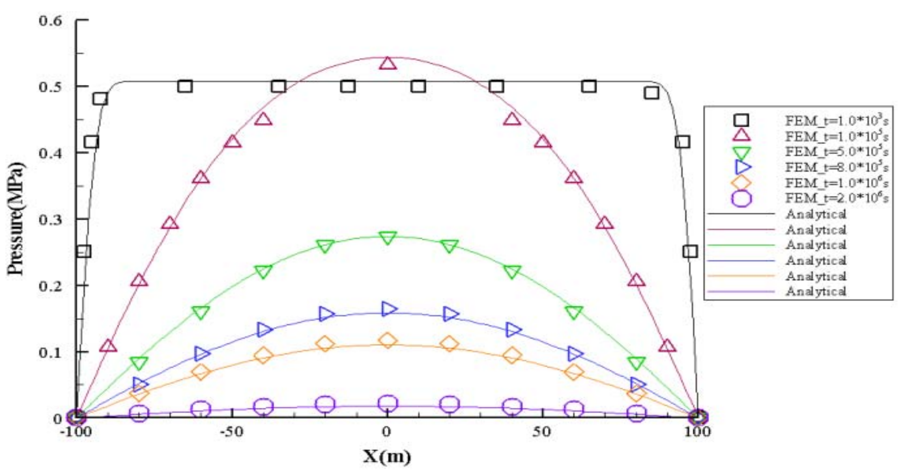
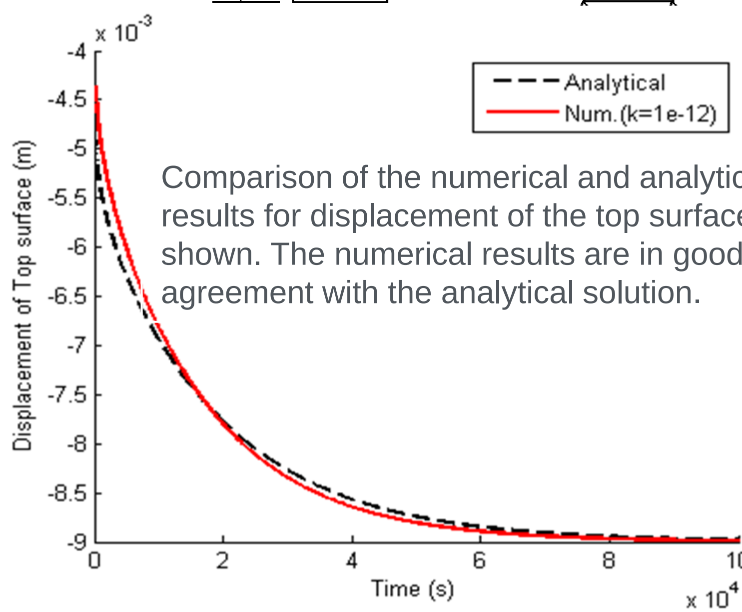
3) Test problem for poroelastic VMIB:
One-D consolidation and Mandel's Problem:
Compression of a poroelastic column, layer of rock and ensuing displacements and pore pressure









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.

3D fracture propagation model using the finite element method with VMIB has been developed

- VMIB has been also been combined with pore pressure, thermal stress & poroelastic effects
- Multiple fractures and propagation modes can be considered
- Results show good agreement with lab data
- Nonlinearity and rock heterogeneity can be considered
- State of the art

Accomplishments, Results and Progress

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Elaborate the three-dimensional multiple internal bond method	3D VMID successfully developed	10/2010
Implement VMIB in 3D FEM and compare model with lab results; verify simulations and add hydraulic fracture routines	VMIB implemented; results compare well with available lab data (literature); pressurization routines developed & tested	10/2011
Implement in a 3D FEM, Hydraulic fracture routine in the VMIB-FEM; Include joint elements; Hydraulic pressurization; Included thermal effects	Thermal effects and pressurization successfully implemented in 3D, joint elements implemented	6/2012
Study and verify thermal and poro effects on fracturing	Thermal effects in 3D, poroelastic effects in 2D (ongoing for 3D)	2013
Application to lab and/or field fracturing experiments	Applied to some lab experiments, block experiment application ongoing	

Future Directions

- key activities for the rest of FY and to project completion (Dec. 2013)
  - Continue to develop the 3-D VMIB numerical model for propagation of multiple fractures in mixed mode (tensile, shear, and tearing) coupled with fluid flow
  - Develop special algorithms to improve accuracy and to enable fracture-natural fracture interaction in 3D, additional poroelastic and thermoelastic analyses
  - The model will be applied to interpretation laboratory large block hydraulic fracture experiment published and planned as part of another project

Summary Slide

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- 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 in 3D
- A 3D poro- and thermoelastic 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
- Thermoelastic fracture propagation in 3D has been successfully modeled

Project Management

Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Actual /Est. End Date
01/1/2009	12/31/2011	6/15/2009	12/31/2013

Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
$685,141	$171,285	$856,000	$780,000	$756,000	$130,000

- The project is slightly behind as we started late (funds not allocated); student recruitment and training required more time, and finally PI and research team moved to another institution and some tasks are pending.

Related Publications

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Huang, K., Zhang, Z., Ghassemi, A. 2012. Modeling three-dimensional hydraulic fracture propagation using virtual multidimensional internal bonds. Int. J. Numer. Anal. Meth. Geomech. DOI: 10.1002/nag.2119.

Zhang, Z. Ghassemi, A. 2010. “Simulation of Hydraulic Fracture Propagation near a Natural Fracture Using Virtual Multidimensional Internal Bonds.” Int. J. Num. Anal. Methods. Geomech. DOI: 10.1002/nag.914.

Huang, K., Ghassemi, A. 2012. Modeling 3D Thermal Fracturing Using Virtual Multi-dimensinal Internal Bonds. Geothermal Resources Council 2012. Reno, Nevada. Sept. 30-Oct.

Min, K.S., Z.Zhang, A.Ghassemi, 2010, “Hydraulic Fracturing Propagation in Heterogeneous Rock using the VMIB Method”, 35th Stanford Geothermal Workshop, Stanford University, California, USA

Min, K.S., Z.Zhang, A.Ghassemi, 2010, “Numerical Analysis of Multiple Fracture Propagation in Heterogeneous Rock induced by Hydraulic Fracturing”, 44th ARMA Conference, Salt Lake, Utah, USA

Min, K.S., K. Huang, A.Ghassemi, 2011, “A Study of Numerical Simulations of Mixed-Mode Fracture Propagation in Rock”, 36th Stanford Geothermal Workshop, Stanford, California, USA

Min, K.S., A.Ghassemi, 2011, “Three-dimensional Numerical Analysis of Thermal Fracturing in Rock”, 45th ARMA Conference, San Francisco, California, USA.