Can We Model Stimulation Processes in Naturally Fractured Geothermal Reservoirs?

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The Naturally Fractured Rock (Reservoir) mass to be “stimulated”

From tankonyvtar.hu
What Controls Stimulation?

NFR Fabric Geometry
NFR Joint Properties
*In Situ* Stresses
Stimulation Rate
Fluids Used in HF
…and some others
Naturally Fractured Rock Mass

Regular, describable systems

Real rock mass
Utica Shale, note the consistent natural fracture fabric

http://blog.aapg.org/learn/?p=659
Natural Fractures

- Natural fractures are largely “closed”
- ...we want to open & connect the natural fractures by HF & HS
- So, NFR properties are very important but we don’t know how to incorporate them easily into models:
  - Cohesion, frictional behavior, ductility
  - Fabric (frequency, orientation, sets, etc.)
  - Fracture compressibility & conductivity
  - Changing stresses & fracture aperture
  - And so on...
How regular is spacing?
What about 3 km deep?
Small scale

Crack gradually disappears

Terminated crack

Offset crack

Incipient crack

...and irregular orientations, varying aperture, different roughness, etc. etc.
A Stochastic Approach?

- Natural fabric variability uncertainty
- Our tools to “see” the fabric in a NFR at depth are very limited (core, acoustics)
- Which parameters are most important?
- Spacing, scale, persistence, distributions...? Of what types?
- We need input from some sophisticated people who understand NFR fabric
**Representative Geometries?**

- Fabric is a highly complex subject
- *Can we choose “representative” geometries for HF simulations?*

Voronoi tessellation  Cross-joints  Cross-cuts

[Images of Voronoi tessellation, Cross-joints, and Cross-cuts]
Joint Mechanical Properties

- Even a “simple” DEM approach needs...
- Cohesion (An “average”? Or local? Scale)
- Friction behavior (= $f(\text{roughness})$)
- Stiffness (invariably = $f(\sigma_n')$)
- Shear stiffness (= $f(\tau, \text{roughness})$)
- Conductivity (= $f(\text{apparent aperture})$)
- Dilation function...

Each parameter is stochastic, linked to others, highly non-linear, $f(\text{scale})$
Are Joints Rough or Smooth?

Source: N. Barton and A. Makurat
Are fractures smooth or rough?
Joint Properties Description

- How to describe the distribution of non-linear parameters like $c'$, $\phi'$?
- Measuring values? Distributions?
  - For each joint set?
  - ...scale effects?
- Clearly, there is no realistic chance to get precise answers
- So, do we determine the dominant parameters and focus only on them?
Rock Mass Stimulation and Well Connection
Interwell Communication...

- Surface casing
- Cement
- Production casing

Wellbores:
- Overburden rocks
- Hydraulic fracture stages

Distance:
- 200-600 m
- 3 - 7 km
- 1500-2000 m

Reservoir:
- Hot dry rock reservoir
The Main Issues...

- *In Situ* Stresses
- Naturally Fractured Rock Mass Properties
- Stimulation Process (rates, pressures, time)
- Exploitation Schedule
In Situ Stresses

- The stress state in the ground is a fundamental factor in stimulation
- A three-dimensional stress state exists

\[
\begin{align*}
\sigma_{HMAX} &> \sigma_{hmin} \\
\sigma_v &\text{ is also a principal stress}
\end{align*}
\]

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Stresses and Stimulation

- Value of $\sigma_3$ dominates HF behavior
- Orientation of $\sigma_3$ controls direction
- Fractures rise, generally
- Deviatoric stress ($\sigma_1 - \sigma_3$) magnitude and stress ratio ($\sigma'_1/\sigma'_3$) control shearing
- And rock & joint properties also...
- ...& stresses change during stimulation!

We understand HF better these days, but not truly predictively.
- We often assume a homogeneous \([\sigma_{ij}]\)
- But we know that initial \(\sigma_h\) stresses are different from bed to bed...
- ...and the transitions are not abrupt
- ...and there are lateral variations too

Assumed \(\sigma_h\) in HF model
Impact of Stress Angle

(a) $\beta = 0$

(b) $\beta = 60^\circ$

(c) $\beta = 90^\circ$

(d) $\beta = 160^\circ$
Pressure Records Show $\Delta \sigma / \Delta t$

- Pressure drops = changes in orientation

![Graph showing pressure changes over time with labels for vertical, horizontal, gradual p increase, sudden drop, gradual drop, and $\sigma_v$.]
Simulation of Stimulation

- The effect of HF and Hydroshearing

\[ \sigma_{\text{hmin}} \]
Shear Dilation

Closed natural fracture
≈ zero conductivity

Remnant shear dilation
= high conductivity

Shear Dilation in Stimulation
Local HF Reorientation...

- $\sigma_n$ increase
- $\sigma_3$ drop in $\sigma_n$
- $\sigma_3$ local stress effects
- $\sigma_3$ natural fractures

- Global orientation
- $\sigma_3$
- $\sigma_{HMAX}$
Locally, fractures follow fabric; globally, fractures are \( \perp \) to \( \sigma_3 \).

Natural fracture system in the rock.
Aperture Impact

\[ \sigma_{xx} = 30 \text{ MPa} \]

\[ \sigma_{yy} = 23 \text{ MPa} \]

Wedged natural fractures

\[ Q = \frac{\gamma}{\mu} \cdot G\alpha^3 \Delta \rho \]
The Stimulated Volume

- Dilated zone
- "Open" aperture zone
- Shear

\( \sigma_{hmin} \)
Scale and Analysis (Simulation)

Wang, Zhao Lin 2011 Engineering 3(1)
Simulation and Uncertainty

- Simulating HF & HS is challenging
- Because of uncertainty...
- ...no one can closely predict stimulation outcomes *a priori* with only simulation
- I believe up-scaled models are vital, and
- ...fabric and system variability must be simplified and better accommodated
- ...real-time monitoring is important
- ...field calibration remains vital
Permeability Evolution

$t=80\ s$  $t=200\ s$  $t=460\ s$
Monitoring Stimulation

- P, T, rate are standard measures...
- Microseismic monitoring is good, but...
- We need **deformations** in order to:
  - Track what is going on at depth
  - Calibrate and use geomechanics models
- Options?
  - Precision tilt measurements
  - Fibre-optics cables in shallow slim holes
  - 3-D active seismics (stress changes)
Conclusions

- Many variables, unknown distributions
- Rock fabric and scale impacts
- Natural & induced stress inhomogeneity
- We will never fully constrain these parameters. So...
- ...predicting stimulation outcomes in the absence of monitoring data is improbable
- ...predicting stimulation outcomes in the absence of calibrations is improbable
What Shouldn't we Model?

- **Tip processes?**
  - Too dominated by local effects
  - Tip process zone is small compared to the HF scale - St. Venant’s Principle

- **Individual joint responses?**
  - Huge constitutive uncertainty for each joint, we must adopt an upscaled “law”
  - Huge changes in fracture conductivity, we must adopt a non-linear “k" = f(damage?)

- **Avoiding deterministic fabric models?**

- **What use is fracture toughness?**
But These are also Challenges!

- Many useful subjects for research and ideas for implementation in the field
- We will never be able to “predict” in a deterministic manner...
- ...but we should get much better at predicting “ranges of outcomes”

Addressing these challenges will drive future EGS implementation, but modesty in our ability to “predict” remains appropriate
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Naturally Fractured Rocks...