Impact of Geological Stress on Flow and Transport in Fractured Media

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Why we care about flow and transport through fractures?

- Fractures often act as either seal or dominate flow paths
There are many studies on flow and transport through rough fractures:

- I. Neretnieks et al., *WRR*, 1982;
- L. Moreno et al., *WRR*, 1988;
- S. Brown et al., *JGR*, 1998;
- Y. Méheust and J. Schmittbuhl, *GRL*, 2000;
- Hele-Shaw Rough fracture

R. L. Detwiler et al., *WRR*, 2000;
- H. Auradou et al., *PRE*, 2001;
- F. Bauget and M. Fourar., *JCH*, 2008;
- Talon et al., *EPL* 2012;
In reality, fractures are always under confining stress: Hydraulic fracturing
Impact of confining stress on fluid flow properties has been widely studied:

K. G. Raven and J. E. Gale, 1985;
D. D. Nolte et al. 1989;
R. W. Zimmerman et al. 1992;
D. R. Briggs, 1992;
**W. A. Olsson and S. R. Brown, 1993**;
A. J. A. Unger and C. W. Mase, 1993;
W. B. Durham and B. P. Bonner, 1994;
C. E. Renshaw, 1995;
V. V. Mourzenko et al., 1995;
N. Watanabe et al., 2008;
L. Zou et al., 2013.

T. Koyama et al., 2008.
Rock physics model – permeability vs stiffness

Pyrak-Nolte and Morris, 2000
Laboratory experiment

Petrovitch et al, 2013
Numerical experiment

Unger and Mase, WRR, 1993;
Mourzenko et al., PRE, 1997;
Rock physics model links flow and seismic data

Seismic equation:
\[ \rho \frac{\partial^2 u_i}{\partial t^2} = \frac{\partial}{\partial x_j} \sigma_{ij} \]

- \( u_i \): displacement vector
- \( \sigma_{ij} \): Cauchy stress tensor

\[ \sigma = \mathbf{C} : \epsilon \]
- \( \mathbf{C} \): fourth order stiffness tensor (function of rock properties)
- \( \epsilon \): infinitesimal strain tensor

\[ \epsilon_{kl} = \frac{1}{2} \left( \frac{\partial u_k}{\partial x_l} + \frac{\partial u_l}{\partial x_k} \right) \]
- \( \epsilon_{kl} \): infinitesimal strain tensor

Flow equation (incompressible, plane Poiseuille flow):
\[ \nabla \cdot \mathbf{q} = 0 \]
- \( \mathbf{q} \): flux per unit depth

\[ \mathbf{q} = -K \nabla P \]
- \( K \): permeability (fn of fracture rock properties)
Joint flow-seismic inversion with rock physics model

Kang et al., 2016, *Water Resources Research*
Hu et al., 2018, *Geophysics*
Objectives of this study

1. Study the impact of the geological stress on flow and \textbf{tracer transport} through a single rough fracture scale to fracture network scale.

2. Develop a parsimonious and effective transport model.
1. Construct a rough fracture surface: self-affine fractal

Numerically generate realistic fracture surface (Fourier synthesis method).
2. Solve the elastic contact problem on rough-walled fractures

\[
\delta = \begin{cases} 
0 & \text{if } \delta = 0 \\
3 \sigma_0 & \text{if } \delta = 3 \sigma_0 
\end{cases}
\]

\[a(x)\]

- \(\delta\): normal displacement
- \(\sigma_0\): standard deviation of aperture values at first contact

Assumptions

1. The medium is linearly elastic.
2. Only consider normal stress.
3. Consider non-local interaction between contact areas.
2. Solve the elastic contact problem

\[ \delta = 0 \]  \hspace{1cm}  \delta = 1.5\sigma_0 \\
\[ \delta = 2.5\sigma_0 \]  \hspace{1cm}  \delta = 3.5\sigma_0 \\

\begin{align*}
\text{aperture} & \quad \text{probability density} \\
\end{align*}

\begin{align*}
\text{aperture} & \quad \text{probability density} \\
\end{align*}
3. Run flow and transport simulation on rough-walled fractures

Fluid flow in the fracture is calculated by assuming
1) Laminar flow
2) The cubic law is locally valid
Which gives a series of parallel plates.

\[ Q_{ij} = -\frac{b_{ij}^3 \Delta a}{12 \mu} \frac{P_j - P_i}{\Delta a} \]

\[ \sum_j Q_{ij} = 0 \]
Pressure field

Normalized flow field

Series of terraces

\[ \delta = 0 \]
\[ \delta = 1.5\sigma_0 \]
\[ \delta = 2.5\sigma_0 \]
\[ \delta = 3.5\sigma_0 \]

Increase in stress

Flow field becomes more tortuous and preferential paths arise as stress increases.
3. Run flow and transport simulation on rough-walled fractures

Aperture field

Flow field
3. Run flow and transport simulation on rough-walled fractures

Low stress case: \( \delta = 0 \)

High stress case: \( \delta = 3.5\sigma_0 \)
Will the increase in confining stress lead to anomalous transport?
The field truth: Anomalous transport is widely observed in subsurface

Photo of Ploemeur field site

Schematic of tracer tests in fractured aquifer

Field tracer breakthrough curve

Fickian transport  vs  Anomalous transport
Signature of Anomalous Transport

![Graph showing mean square displacement vs time for Fickian, superdiffusive, and subdiffusive transport.]

- Fickian transport: $1$
- Superdiffusive transport: $1 + \alpha$
- Subdiffusive transport: $1 - \alpha$

The graph illustrates the mean square displacement over time for different transport regimes, with Fickian transport being represented by a straight line, superdiffusive by a line with a slope of $1 + \alpha$, and subdiffusive by a line with a slope of $1 - \alpha$.
4. Analyze flow and transport characteristics with respect to stress

We can clearly observe transition from Fickian to non-Fickian (anomalous) transport.
5. Develop a predictive transport model

Model development: Spatial Markov Model

3D pore scale

Kang et al., *GRL.*, 2014

Darcy scale

Le Borgne et al., *PRL.*, 2008

Field scale

Kang et al., *WRR.* [2015]
5. Develop a predictive transport model

Directly map multiscale heterogeneity onto particle velocity probability distribution: **velocity heterogeneity**

\[ \psi_0 (\tau) \]

\[ \tau_n = \frac{dx}{v_n} \]

\( \tau_n \): follows the transition time distribution (\( \psi_0 (\tau) \)) that follows truncated power-law

\[ \psi_\tau(t) \sim \frac{\exp(-\tau_0/t)}{(t/\tau_0)^{1+\beta}} \]
5. Develop a predictive transport model

**Velocity correlation structure is Markovian in space**

We formulate correlated CTRW that honors velocity heterogeneity and correlation.

\[
x_{n+1} = x_n + dx, \quad t_{n+1} = t_n + \tau, \quad \tau = \frac{dx}{v}
\]

\(\tau_n\) : characterized by the transition time distribution \(\psi_0(\tau)\)
and one-step transition probability density \(\psi_1(\tau|\tau')\)

5. Develop a predictive transport model: Correlated CTRW

Kang et al., EPSL. (2016)
Visual laboratory experiment on stressed rough fracture

Field trip to obtain natural fracture surfaces
Experimental set up: Dynamic imaging with transparent micromodels
Laboratory experiment results: rough fracture

Low stress

High stress
Part 1 Conclusions

1. Stress induces anomalous transport at a single fracture scale: transition from Fickian to non-Fickian

2. Spatial Markov model can predict anomalous transport through stressed rough fractures.
Impact of stress on natural fracture network scale flow and transport

Natural fracture networks of the Bristol fractured reservoir

- A natural fracture network is extracted from the geological map of a rock outcrop.
- Aperture values are sampled from a aperture distribution that follows log normal distribution with mean 1 [mm] and variance 1.
- Aperture values are randomly assigned to each link.
Impact of stress \textit{magnitude} on fracture network-scale transport

\[ \sigma'_x = 3 \text{ MPa}, \sigma'_y = 3 \text{ MPa} \]
Impact of stress magnitude on fracture network-scale transport

\[ \sigma'_x = 15 \text{ MPa}, \ \sigma'_y = 15 \text{ MPa} \]
Impact of stress orientation on fracture network-scale transport

\[ \sigma'_x = 15 \text{ MPa}, \quad \sigma'_y = 5 \text{ MPa} \]
Impact of stress *orientation* on fracture network-scale transport

\[ \sigma'_x = 5 \text{ MPa}, \sigma'_y = 15 \text{ MPa} \]
Geomechanical modelling of fracture networks

- The Cauchy linear momentum equation is solved using finite-discrete element method (FEMDEM) (Munjiza, 2004).

- Joint constitutive model (JCM) captures joint closure, shearing, shear dilatancy by taking fracture roughness into account.

Example of an aperture field under stress

Aperture field: no stress, $\sigma_x = 15$ MPa, $\sigma_y = 5$ MPa

- For each scenario, an ensemble of 20 realizations are generated and studied.
Solve for fluid flow through stressed discrete fracture networks

Fluid flow in the fracture is calculated by assuming
1) Laminar flow
2) The cubic law is locally valid
Which gives a series of parallel plates.

\[ Q_{ij} = -\frac{a_{ij}^3}{12\mu} \frac{P_j - P_i}{l_{ij}} \]

\[ \sum_j Q_{ij} = 0 \]

Boundary conditions:
1. No flow on top and bottom boundaries
2. Constant pressure on left and right boundaries
Solve pressure equation to obtain flow field

Pressure field: 15MPa-5MPa

Flow field: 15MPa-5MPa
Run tracer transport simulation on obtained flow fields

- Flux-weighted Injection at the inlet:
  \[ N_{i0} = N_p \frac{Q_{i0}}{\sum_{i_0} Q_{i0}} \]

- Complete mixing at intersections:
  \[ p_{ij} = \frac{|u_{ij}|}{\sum_k |u_{ik}|} \]

- Particle tracking simulation:
  \[ x_{n+1} = x_n + \ell_n e_n, \]
  \[ t_{n+1} = t_n + \frac{\ell_n}{v_n}, \]

Kang et al., Adv. Water Resour., 2017
Impact of stress orientation on fracture network-scale transport

\[ \sigma'_x = 5 \text{ MPa}, \sigma'_y = 15 \text{ MPa} \]  
\[ \sigma'_x = 15 \text{ MPa}, \sigma'_y = 5 \text{ MPa} \]
Stress induces anomalous transport in fracture network-scale transport

We can observe features of non-Fickian (anomalous) transport:

- Emergence of late-time tailing
- Anomalously early arrival of tracers for the 15MPa-5MPa case.
What are the origins of anomalous transport?
Origin of the emergence of late-time tailing

- Stress significantly increases small aperture values
Origin of the emergence of late-time tailing

Aperture distributions

- Geologic stress broadens aperture distribution
- Increase in the variance of the aperture distribution makes heterogeneous velocity field
Origin of the anomalously early arrival

Normal stress on fractures

\[ \sigma'_x = 5 \text{ MPa}, \sigma'_y = 15 \text{ MPa} \]

\[ \sigma'_x = 15 \text{ MPa}, \sigma'_y = 5 \text{ MPa} \]

Shear dilation

\[ \sigma'_x = 5 \text{ MPa}, \sigma'_y = 15 \text{ MPa} \]

\[ \sigma'_x = 15 \text{ MPa}, \sigma'_y = 5 \text{ MPa} \]

- Stress anisotropy opens / closes different fracture sets
- Interplay between fracture geometry (connectivity, direction) and stress condition controls shear dilation
Flow values are normalized with the mean flow rate of the no stress case.

Shear dilation causes strong preferential paths.
Can we develop a parsimonious upscaled transport model?
Impact of Stress on Lagrangian Velocity Distributions

Geologic stress has major impacts on Lagrangian velocity distribution.
Impact of Stress on Lagrangian Velocity Correlation

Conditional correlation length:

\[ C(x|\ln v_0) = \int_{-\infty}^{\infty} \left| P(\ln v|\ln v_0, x) - P(\ln v, \infty) \right| d\ln v \]

\[ x_C(\ln v_0) = \int_0^{x_{\max}} \frac{C(x|\ln v_0)}{C(0|\ln v_0)} dx \]

Ref: Le Borgne et al., 2007, WRR
The model with a single correlation length shows good predictability except for the 15MPa-5MPa scenario.
Emergence of strong correlation length due to shear dilation

Two correlation length model is proposed:

\[ T_{ij} = a_i \delta_{ij} + (1 - a_i) \frac{1 - \delta_{ij}}{N - 1} \]

where \( a_i \) is a function of velocity class.
We honor the emergence of strong velocity correlation with the two correlation length model.

The model nicely predicts 15MPa-5MPa scenario.

Kang et al., *submitted* (2018)
Conclusions

1. Interplay between stress and fracture geometry can induce anomalous transport in fractured media.
2. Stress fundamentally changes velocity correlation and velocity heterogeneity.
3. Spatial Markov model with dual correlation length can predict anomalous transport through fractured media.
Impact of Variable-Density Flow on the Value-of-Information of Pressure and Concentration Data for Saline Aquifer Characterization

Seonkyoo Yoon, Peter Kang
Thank you

Research website: www.pkkang.com