Subsurface
Processes
Lab

Flow and Geometry Control the Onset of Jamming in Fractures with High-Solid-Fraction Fluids

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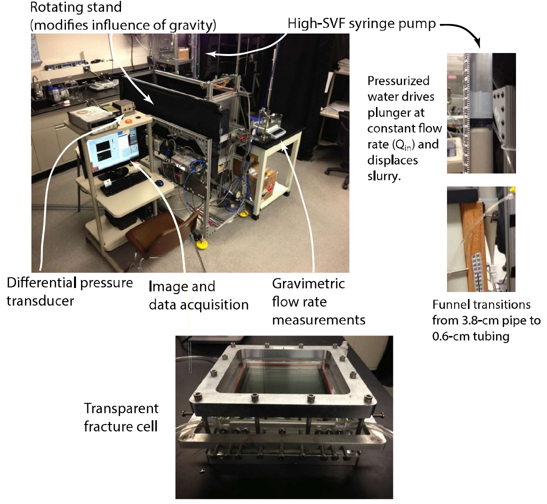
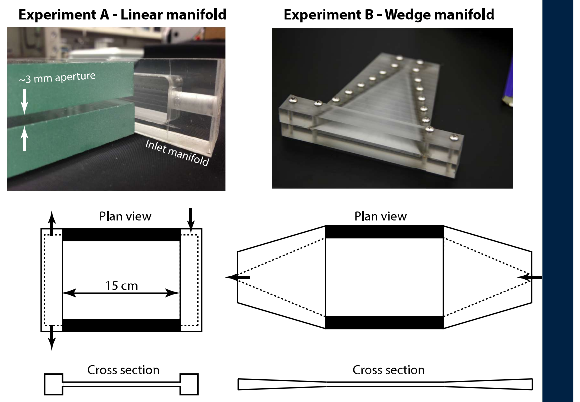
Introduction

- Fluids containing a large fraction of suspended solids are common in the subsurface (e.g., environmental remediation, hydraulic fracturing and magma).
- Such fluid-solid mixtures behave as non-Newtonian fluids with a rheology that depends on the carrying fluid and the characteristics of the suspended solids (e.g., geometrical and physical properties as well as concentration).
- Interactions between carrier fluid, suspended solids, and pore walls can lead to jamming of the solid phases, where the velocity of the solid decreases locally to zero causing a rapid decrease in permeability as the fluid is forced to flow through the pore space within the immobilized solid.
- We present results from experiments and numerical simulations that quantify the flow of non-Newtonian high solid content fluid in an analog parallel-plate fracture and explore the dependence of rheology and jamming on flow conditions and fracture geometry.

Experiments in transparent analog fractures allow direct measurement of fracture aperture and flow fields

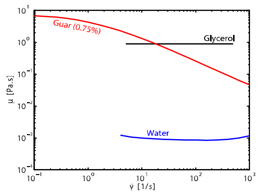


Inlet boundary conditions controlled by manifold geometry

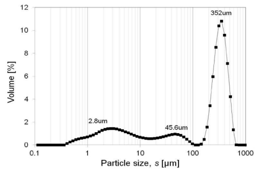


Fluid rheology in the absence of solid

- Guar carrying fluid exhibits:
  - Power-law viscotisy at large shear rates.
  - Newtonian behavior at lower shear rates.

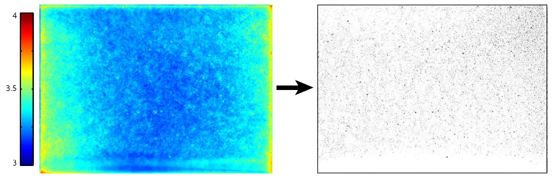


- Experimental flow rates in our experiments correspond to strain rates less than 0.1 s^{-1}, therefore the guar-based carrier fluid is within its Newtonian regime where one can assume a viscosity of ~8 Pa·s



Solids consist of silica sand with multimodal particle size distribution

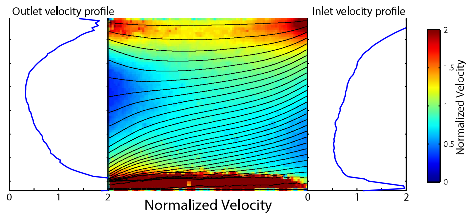
Particle Image Velocimetry (PIV) quantifies evolving velocity fields



CCD images lead to quantitative measurements of light absorbance over the entire flow field

High-pass filtering and thresholding yields binarized image of discrete sand grains

- Cross-correlation between sequential images leads to robust velocity estimates over the entire flow field.



- Velocity fields are normalized by the mean uniform velocity (Qin/cross sectional area) for a given flow rate.

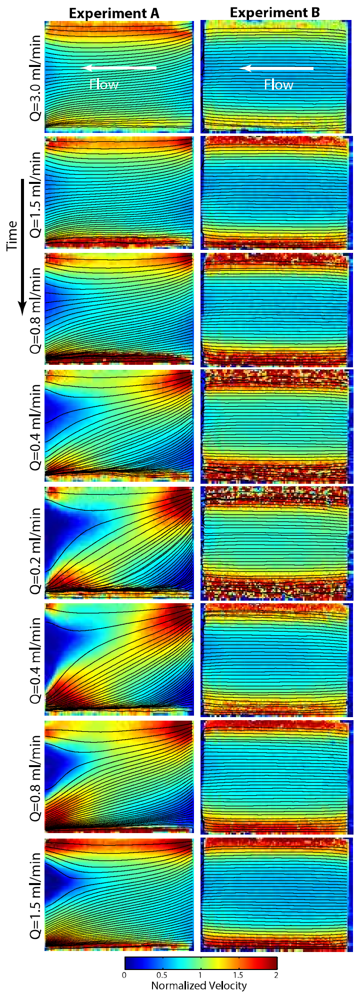
Flow-through experiments with sequential steps in flow rate

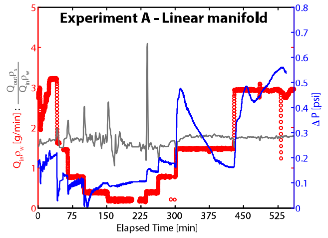
Experimental procedure

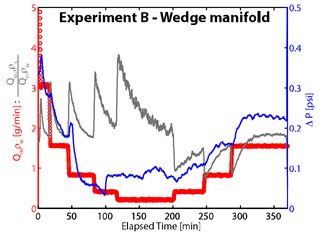
- Fracture initially filled with solid-free carrier fluid.
- Inlet manifold completely filled with slurry before initiating flow through the fracture.
- Flow through the fracture proceeded through a series of discrete flow rates (3, 1.5, 0.8, 0.4, 0.2, 0.4, 0.8, 1.5, 3 ml/min).
- Each flow rate maintained until the differential pressure reached ~steady state.

Experimental results

- Velocity field evolves non-uniformly as flow rate changes:
  - Initially, flow is nearly one-dimensional with higher velocities observed along the two no-flow boundaries (for both experiments A and B).
  - As flow rate decreases, a low-flow region develops near the center of the outlet manifold (experiment A).
  - At Q=0.2 ml/min, the solids become jammed (V~0) in a large region near the outlet manifold.
  - As flow rates increase, the jammed region persists, but gradually decreases in size.
- Behavior of velocity field for experiment B remains nearly one-dimensional throughout experiment.
- High velocity regions observed in experiments A and B, along no-flow boundaries
  - Enhanced light absorbance hints at a possible explanation: smaller size particles absorb more light than coarse sand, which suggests a nonuniform distribution of fines in the flow field .
  - The effective viscosity of the slurry depends upon the concentration and particle size of the solids: larger particles and higher SVF → higher μ.
  - Variability in SVF across fracture may be due to sorting of solids in the inlet manifold (A) or the hydrodynamics of the flow field within the slot (B).
- Onset of jamming observed as significant decrease in velocity and divergence of streamlines.
- Sorting of particles near no-flow boundary occurs, independent of manifold geometry.





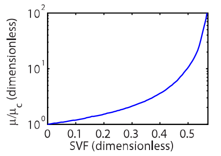


CFD simulations support interpretation of experiments

- Use particle-in-cell (PIC) approach to minimize advection discretization errors
  - Tracks the fluid within the fracture using Lagrangian marker particles that move with the fluid velocity
- Each time step:
  - Properties of the particles are projected onto an Eulerian grid
  - Local rheological properties of the fluid calculated for each cell of the grid using the local value of the SVF and the viscosity correction
  - Grid-based pressure and velocity fields are obtained
  - Updated velocities are then interpolated back onto the Lagrangian particles
  - Particle positions are updated for the next time step

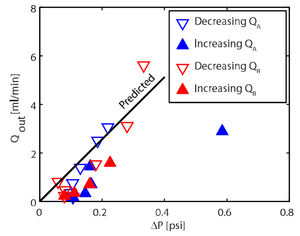
Rheological model for the slurry

- Rheological model for the slurry developed by Lecampion and Garagash (2013, JFM, submitted)
- Fully developed solution for flow between two plates for:
  - Newtonian carrier fluid and mono-dispersed solid particles
  - Average flux between two plates corresponds to the Newtonian (cubic law) solution with an effective viscosity corrected for the SVF.
- Lecampion and Garagash (2013) predict that the flow of a slurry between two plates will obey the Newtonian (cubic law) solution with the effective viscosity corrected as below.



Simulations of homogeneous flow in a slot

- Experimental flow rates corresponded to strain rates less than 0.1 s^{-1}. Consequently, the guar-based carrier fluid is within its Newtonian regime and we take its viscosity to be 8 Pa·s.

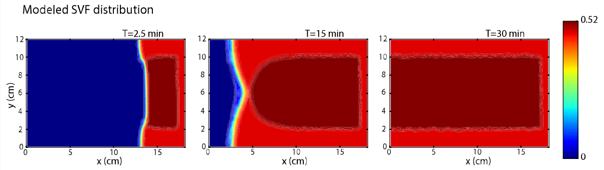


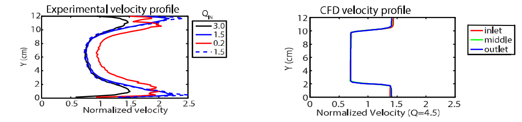
Experimental observation compared with model prediction of pressure difference between inlet and outlet as the flow rate is varied. The model and experiment are in excellent agreement for decreasing flow rate (down triangles) for both experiments A and B. The experimental results show some evidence of a yield stress (approaching zero flow at a finite pressure differential).

Simulations of heterogeneous flow in a slot

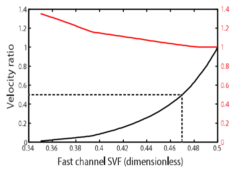
- Experiments exhibited a consistent heterogeneous flow field, despite the injected fluid being homogeneous in composition. Using our CFD model, we attempted to match this behavior by introducing heterogeneity into the slot due to:
  1) Blockages into the manifold at the inlet and outlet
  2) Variations in aperture of the slot
  3) Heterogeneity in the SVF field within the inlet manifold
- Model results indicate that only heterogeneity in the upstream SVF could explain the velocity field:
  - CFD model indicates that changes in upstream SVF values are preserved during flow
  - Sustained variations in the flow field downstream of the inlet manifold persist all the way to the outlet manifold
  - A reduction of as little as 3% SVF can lead to a factor of two increase in velocity within the low SVF channels over that in the higher-SVF central flow region.

Modeled SVF distribution





Experimental velocity field indicates that velocities are approximately doubled in two regions near no-flow boundaries (top and bottom 2cm-regions). CFD modeled velocities can reasonably explain the velocity difference between the central and edge regions when assuming that low SVF channels have an inlet SVF of 0.47 and the central region an inlet SVF of 0.515.



The black curve shows the ratio of the flow rate in the central slow channel of the heterogenous slot to the two faster low-SVF channels of 2 cm width. The red curve shows the predicted ratio of total flux in the heterogeneous scenario compared with the assumption of a homogeneous SVF of 0.5. The dashed line indicates an SVF of 0.47 which approximates the experimental observation of velocity doubling in the fast channel zones.

Conclusions

- Flow of high SVF fluids are very sensitive to boundary conditions and heterogeneity in solid volume fraction within the flow field.
- Sorting of solids within the flow field results in heterogeneous SVF concentrations, resulting in local viscosity variations, which strongly influence the velocity field within the fracture.
- Flow configurations that include a stagnation zone wihin the flow domain lead to jamming of the solids at low velocities resulting in hysteresis in the effective permeability of the fracture.
- CFD simulations using a rheological model that assumes a Newtonian carrying fluid predicts the observed behavior reasonably well suggesting that quantifying the low-strain-rate behavior of the carrying fluid is critical in predicting the effective behavior of these fluids.