Coupling Fracture and Fluid Pressure Using Phase-Field Modeling

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Motivation

Fluid-driven crack propagation is present in many physical applications (CO_2 sequestration, groundwater contamination, fluid induced fault activation):

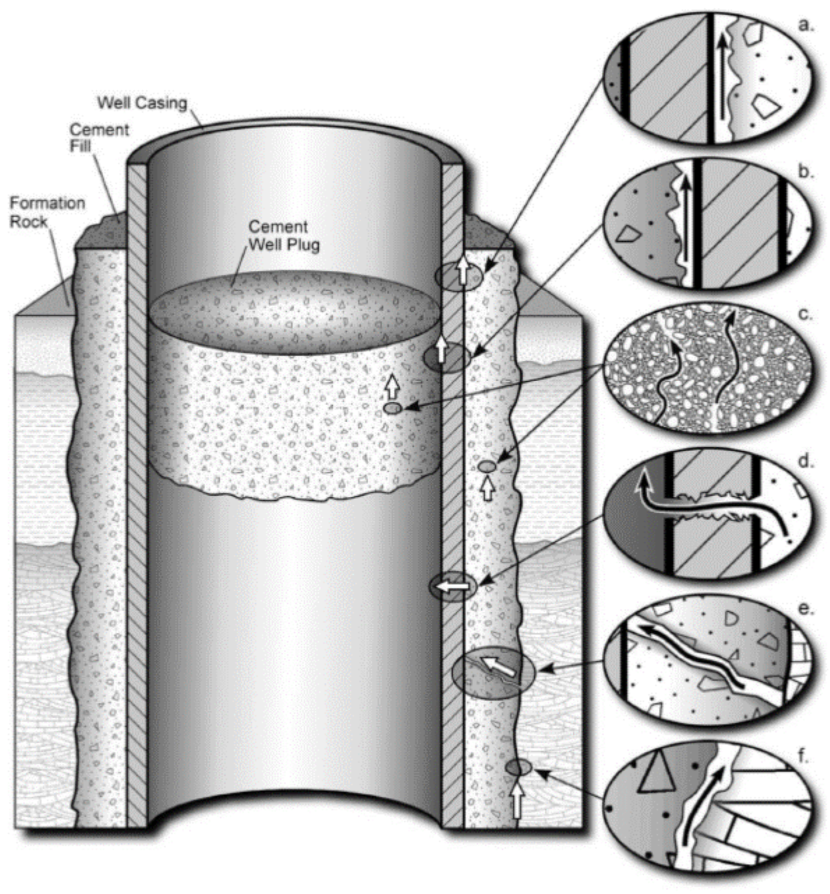


Figure 1: Figure caption

An encased borehole may be vulnerable to many types of fracture/ failures in the presence of fluids under high pressures, which lead to leaks.

Introduction

Phase-field - a Variational Approach to Fracture:

$$\Psi(\epsilon, \Gamma) = \int_{\Omega} \Psi_e(\epsilon) d\Omega + \int_{\Gamma} G_c d\Gamma$$

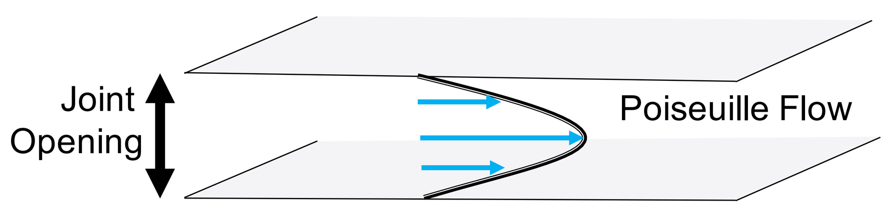
Total Potential = Strain Energy + Fracture Energy

Phase-field approximation of fracture is solved during each time-step by minimizing the fracture energy. It is a preferred model for fracture for several reasons:

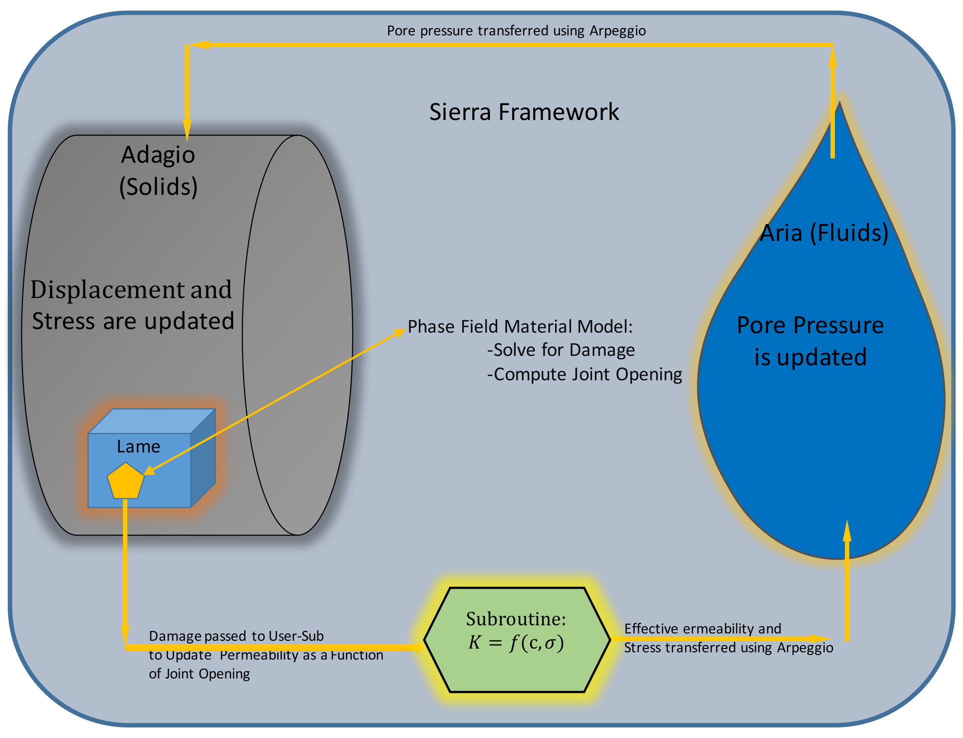
- Smooths sharp discontinuities to scalar damage variable,
- Robustly models branching, initiation, and 3D cracks,
- No need for a-priori location of crack,
- Avoids the need for adaptive mesh refinement.

Two-Way Coupling of Fluid Flow and Fracture:

- High fluid pressures → Fractures
  - Hydrostatic pressure used to update total stress
- Presence of Fractures → Fluid Flow
  - Joint opening used to update permeability
  - Onset of Poiseuille flow within fractures

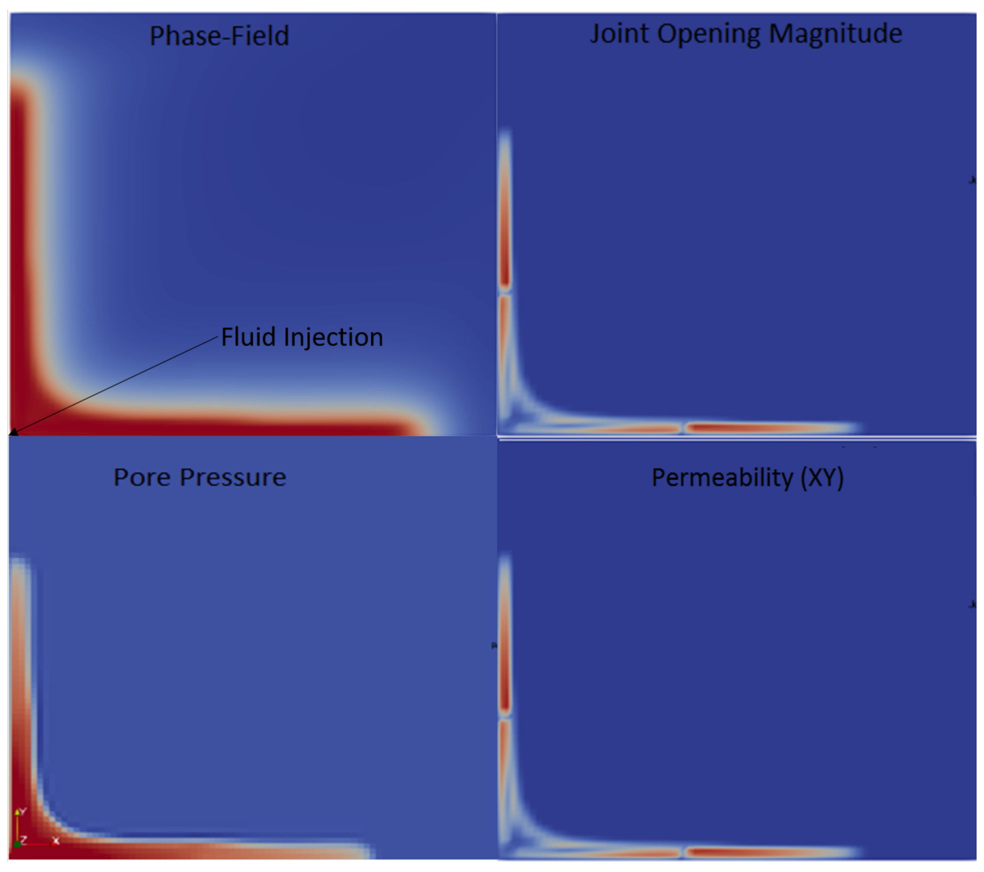


Coupling



- Separate modules within Sierra solve the fluid and solid mechanics independently.
- Arpeggio transfers the fields of interest between the modules in order to achieve the two-way coupling.
- A material model was written to handle the phase-field solution, and to compute the joint opening, which is used to modify the material's permeability.

Results



The results of a numerical simulation in which fluid volume is injected into the bottom left corner of a quarter-symmetric mesh:

- Top Left: the phase-field, or fractures that have propagated
- Top right: the corresponding joint opening of the fractures
- Bottom right: the permeability as a result of the joint opening
- Bottom left: the fluid pressure distribution within the fractures

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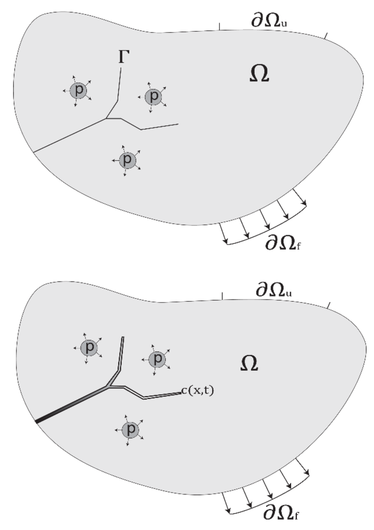
Results cont.



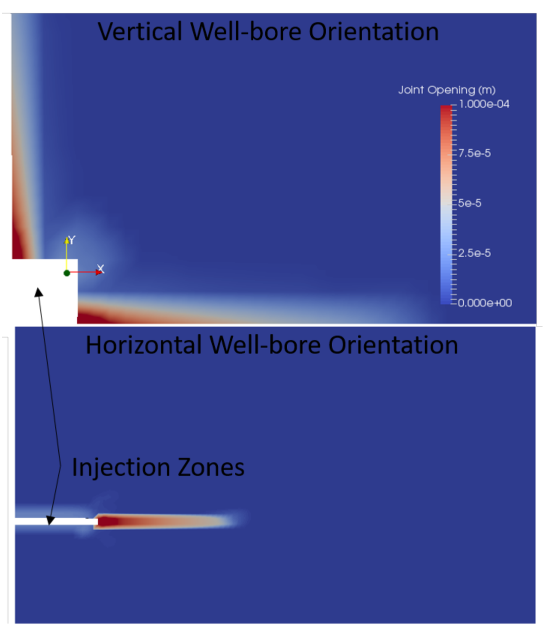
Depiction of boundary conditions in a discontinuous (top) and phase-field (bottom) representation of fluids in an arbitrary body.

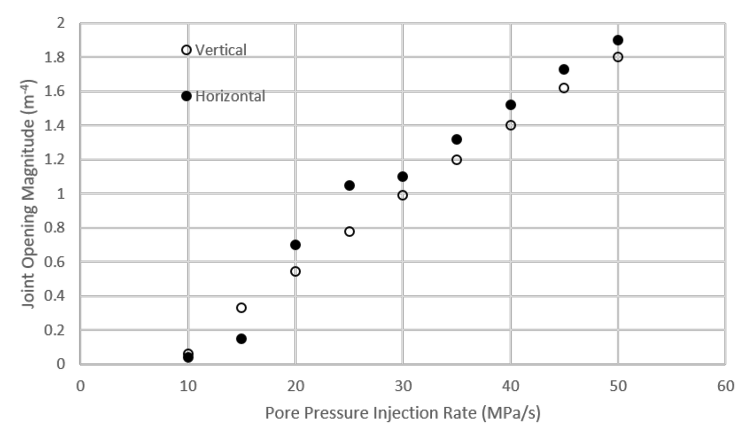
Table below shows the material and numerical parameters used for the simulation of fluid injection through wellbores. Material parameters are representing limestone.

Parameter	Symbol	Value
Young's modulus	E	10 GPa
Density	ρ	2560 $\frac{kg}{m^3}$
Critical Fracture Energy	G_c	100 $\frac{J}{m^3}$
Fracture Length	l_0	0.02 m
Poisson's Ratio	ν	0.155
Biot's coefficient	b	1

Effect of Wellbore Orientation on Joint Opening Magnitude

The maximum joint opening is monitored over time using many fluid volume fluxes in both scenarios.
The results, shown below, indicate that the joint opening is strongly correlated with the rate of injection, but not with wellbore orientation.





Future work

- Introduce a physic-based relationship between joint opening and permeability
- Implement this coupled system within Kayenta (Sandia cap-plasticity material model)