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Title:	Implicit and explicit coupling in thermohydrological-geomechanical numerical methods
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Implicit and explicit coupling in thermohydrological-geomechanical numerical methods

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Abstract

We compare fully implicit and partially explicit coupling between stress and fluid flow in a scenario such that the permeability is a strongly dependent function of the stress state. In this scenario, permeability changes are driven by tensile stresses resulting from the injection of cold fluid into the base of a vertical column of hot rock. A high permeability zone propagates from the base upward, and numerical truncation errors associated with increased time step or decreased spatial resolution result in front propagation speeds that are nearer the front speed in a model with no stress-induced permeability increase. We explain this effect by considering the relative velocities of the thermal and material failure propagation fronts.

Motivation

Many physical processes of interest for applications involve interconnected aspects of heat transfer, fluid flow, and geomechanics. Examples include permeability enhancement via high pressure fluid injection (i.e., "frakking") as employed in the oil industry, thermal fracturing due to pumping of cold fluid into hot rock as in "hot, dry rock" geothermal energy applications, and the interaction between mechanical stability and chemical erosion of wellbore casings in zones of CO_2 sequestration. The equations describing fluid flow and stress in such systems are highly coupled and often display strongly nonlinear behavior. Considerable computational savings result from setting the permeability/stress coupling terms in the stiffness matrix to zero, i.e., solving the flow and stress equations in a semi-explicit manner. However, it is then important to understand the origin and magnitudes of the resulting error.

Material failure model

We have incorporated a simplified model of permeability enhancement resulting from tensile opening of flowing fractures. The conceptual model comprises three sets of fractures, in each of the x_1x_2, x_2x_3, and x_3x_1 coordinate planes. Let σ_k be the component of stress normal to the x_ix_j plane, where $\sigma_k < 0$ indicates a state of tension. Then the permeabilities $k_{i,j}$ in the $x_{i,j}$ directions are calculated according to

$$k_{i,j} = \frac{k_{i0,j0}(\gamma_{i,j} - 1)max[0, min[\sigma_{ex}, \sigma_{ex,\gamma}]]}{\sigma_{ex,\gamma}} + k_{i0,j0} \quad (1)$$

where

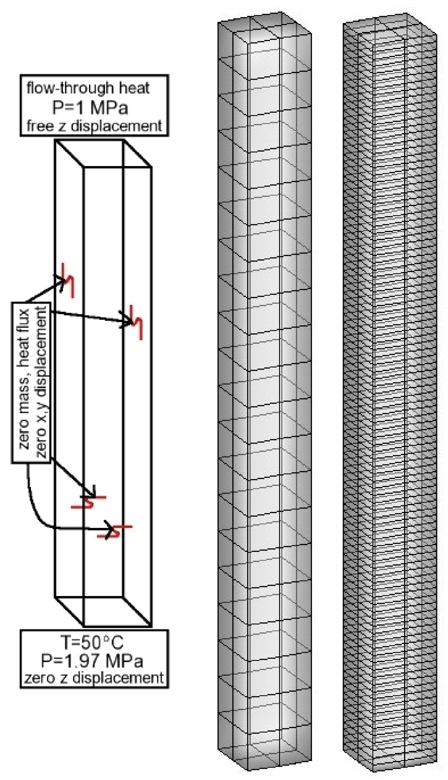
$$\sigma_{ex} \equiv -min(\sigma_k + T, 0) \quad (2)$$

and

$$\sigma_{ex,\gamma} \equiv \sigma_{ex} + W. \quad (3)$$

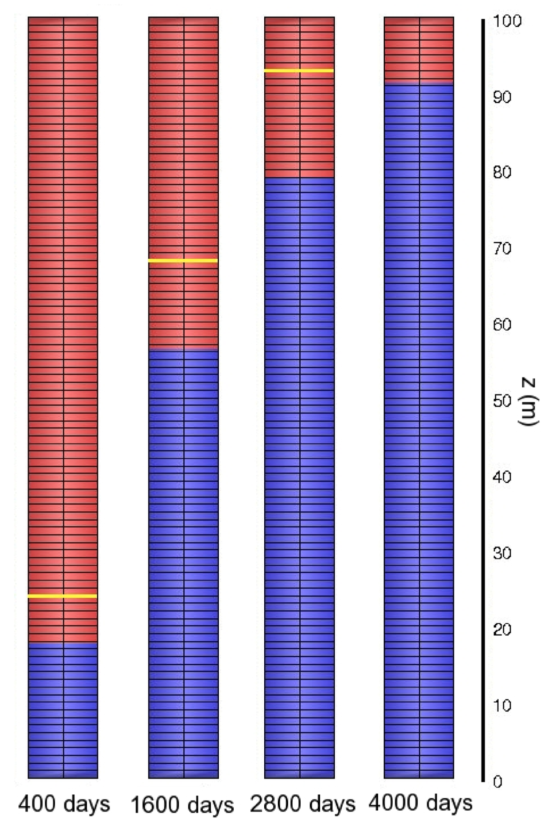
In these equations, $\gamma_{i,j}$ are user defined maximum factors by which to multiply the permeabilities, T is the amount by which the absolute value of the tensile stress must exceed zero in order for material failure to occur, and W is the amount of stress in excess of σ_{ex} at which the $k_{i,j}$ become $\gamma_{i,j}k_{i,j}$. As an illustration, consider a situation where the σ_1 component of the stress tensor becomes tensile and less than $-T$. In this case the k_2 and k_3 components of the permeability will be increased along a linear ramp of width W, ending at the values γ_2k_2 and γ_3k_3. Nonlinear material behavior can also be approximated by reducing the Young's moduli in the coordinate directions by user specified factors.

Grids and boundary conditions



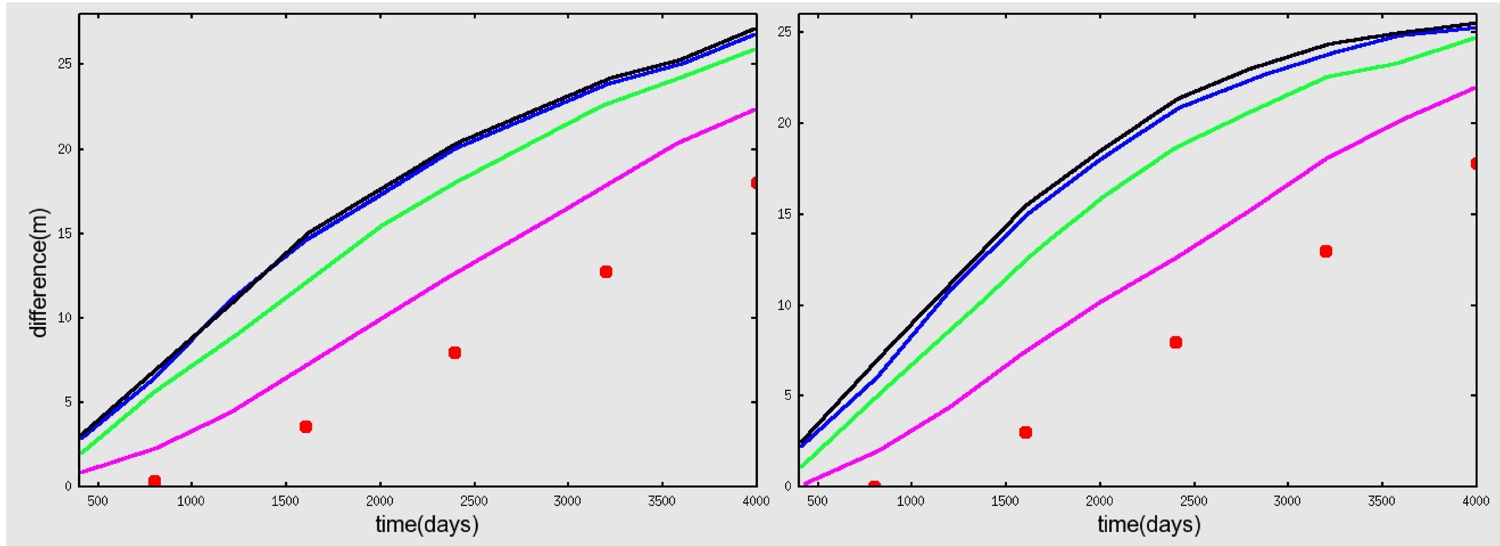
We model a scenario in which cold fluid (50°C) is injected at the base of a column of hot rock (150°C). Because the sides of the column are held fixed in the horizontal (x and y) directions, strong tensile stresses form around the thermal 100°C propagation front. These stresses create an upward propagating zone of raised permeability (from the initial value 10^{-13} to 10^{-12} m^2). To study the effects of altering the grid resolution, we employ grids of one meter and five meter vertical resolutions. For each grid we run the simulation with time step sizes ranging from one to eight hundred days.

Sample simulation



Simulation results on the fine grid with a time step size of one day. The blue region represents fluid colder than 100°C and the red region represents fluid hotter than this temperature. The yellow line shows the position of the fracture front, as measured by the permeability being above its initial value of 10^{-13} m^2 at locations below this front. The thermal front propagates significantly slower if the simulation is run again with the failure model disabled. The front reaches only about 66 m in 4000 days for this case.

Effect of explicit coupling



To distinguish between the effects of numerical dispersion and explicit coupling, we plot the difference between the thermal front position with the fracture model turned on and the position in a corresponding simulation without the fracture model. The left figure shows differences on the coarse grid for time step sizes of one day (black), ten days (blue), one hundred days (green), four hundred days (pink), and eight hundred days (red). The curve corresponding to eight hundred days has less output because of the large time step size, and is hence plotted only as dots. The figure on the right shows results from the same simulation, but run on the fine grid. Both plots show that increasing the time step size decreases the differences between the hydro-mechanical and flow-only thermal front positions.

Explanation

As the time step size approaches zero, the results of explicit and implicit stress-flow coupled simulations converge. For small time step sizes, the zone of high permeability always preceeds, i.e., is shallower than, the thermal front as both fronts propagate toward the surface at roughly the same speeds. For large time step sizes, however, the thermal front must propagate for longer amounts of time before the failure front position is updated. Because the zone of high permeability starts at the base of the system and ends at the position of the failure front, the thermal front must travel through more low permeability material, on average, as the time step size is increased. Therefore, the velocity of the thermal front decreases with increasing time step. In the limit of "infinitely" large time step size, permeabilities are never updated under explicit coupling and the thermal front propagates with the same speed as in the simulation that has the failure model turned off.

Conclusions

- *Increasing time step size and decreasing grid resolution both increase the error associated with solving stress and fluid flow equations in a semi-explicit manner.*
- *The effect of the error is, in both cases, to decrease differences between the hydromechanical and flow-only simulation results.*
- *The effect due to the time step size can be simply explained by considering the relative positions of the thermal and material failure fronts as the time step size is increased.*