Numerical modeling of injection induced seismicity in a damaged rock domain with fracture manifolds

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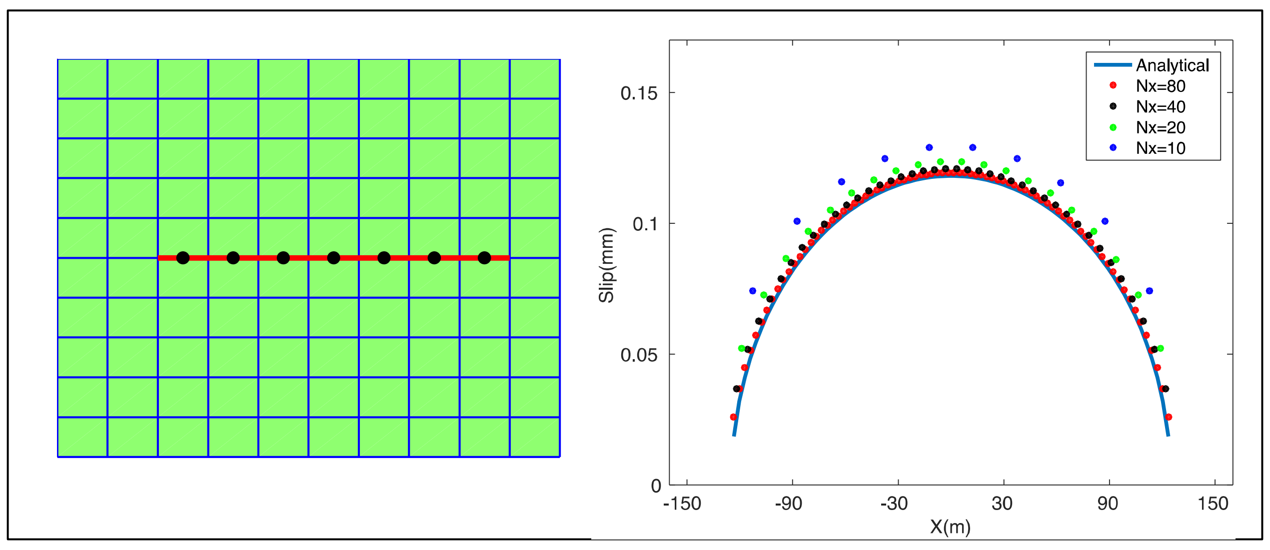
Abstract

A finite volume method based numerical model is developed to capture the failure events in a stressed domain and the subsequent effect on the fluid pressure and volume along the fractures. The failure criterion is based on the static/dynamic friction law of Coulomb friction forces and the slip solution along with elastic displacements of the domain are calculated for discrete volume segments. A subsequent evolution of the pressure field due to failure induced opening of fractures is also obtained. The aperture changes along the fracture manifolds are calculated as function of shear dilation slip solutions. The change in fracture volume due to shear dilation is modeled using a time dependent volume change equation, which is characterized by a specified timescale. This leads to a stable numerical scheme without having to resolve the geo-mechanical timescale.

Slip Elements

Each predefined fracture plane has been discretized into finite segments. On each segment, the traction and compressive forces are calculated to check the failure criterion. Once the failure limit is reached, the next time step is resolved using an additional slip solution on the failure segment along with the linear elastic solution in the domain. Here rather than resolving the dynamic process of this slip solution, a final static equilibrium is calculated. The following figures shows the grid discretization and the comparison of the numerical slip solution with analytical result for a constant stress drop on a fault.



The governing equation solved here are as follows

$$\int_{\Omega} (\nabla \cdot \tilde{\sigma} + \vec{f}) d\Omega = 0 \quad (1)$$

$$\int_{d\Omega} \tilde{\sigma} \cdot d\vec{A} + \int_{\Omega} \vec{f} d\Omega = 0 \quad (2)$$

$$\tau(s_x, s_y) = (S_0 + \mu_d \sigma_c(s_x, s_y)) \quad (3)$$

Here the equation (1) integrates the stress equilibrium equation over a finite volume segment and the equation (2) represents the equilibrium between the stress forces on the domain boundary with the volume forces. The equation (3) restores shear traction force to the friction limit.

Volume Relaxation

The shear failure leads to the increase of aperture of the fracture. This increases both transmissivity and storativity of the fracture. The instantaneous increase in this storativity or void aperture of the fracture is difficult to resolve numerically in the fluid flow solver. A volume relaxation timescale is used here to model the time taken by the fluid to occupy this newly created volume. The equation (5), (6) and (7) represent the governing equations and the volume relaxation model for fluid flow solver.

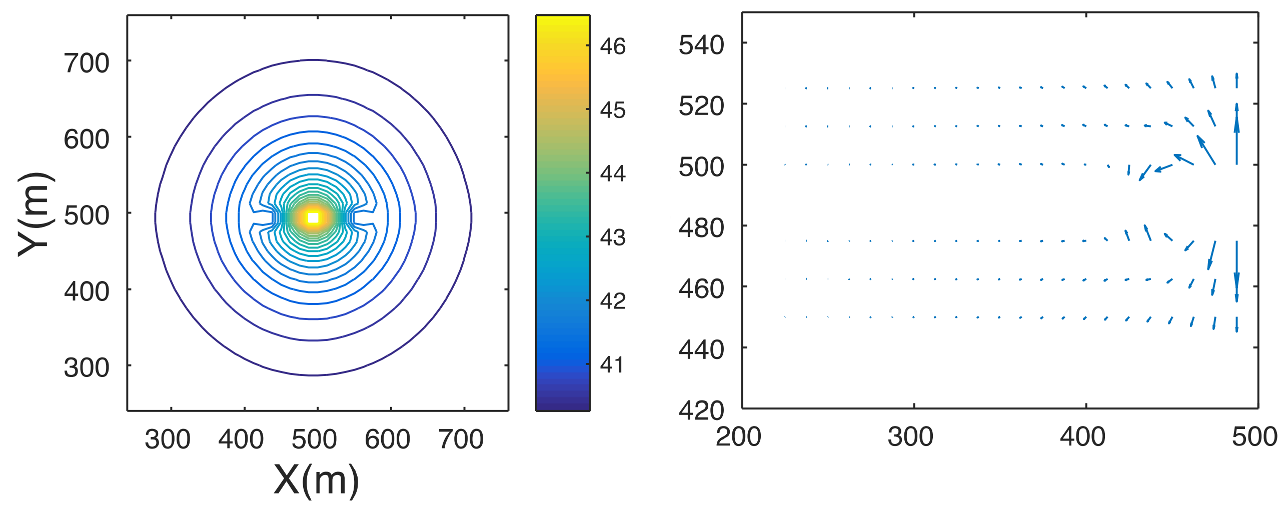
$$\frac{\partial E^i}{\partial t} - \nabla \cdot \left(\frac{b^i \boldsymbol{k}^i}{\mu} \cdot (\nabla p^i - \rho g) \right) + \Psi^{i \to d} = q^i, \quad (5)$$

$$\frac{\partial \phi^d}{\partial t} - \nabla \cdot \left(\frac{\boldsymbol{k}^d}{\mu} \cdot (\nabla p^d - \rho g) \right) + \Psi^{d \to i} = q^d \quad (6)$$

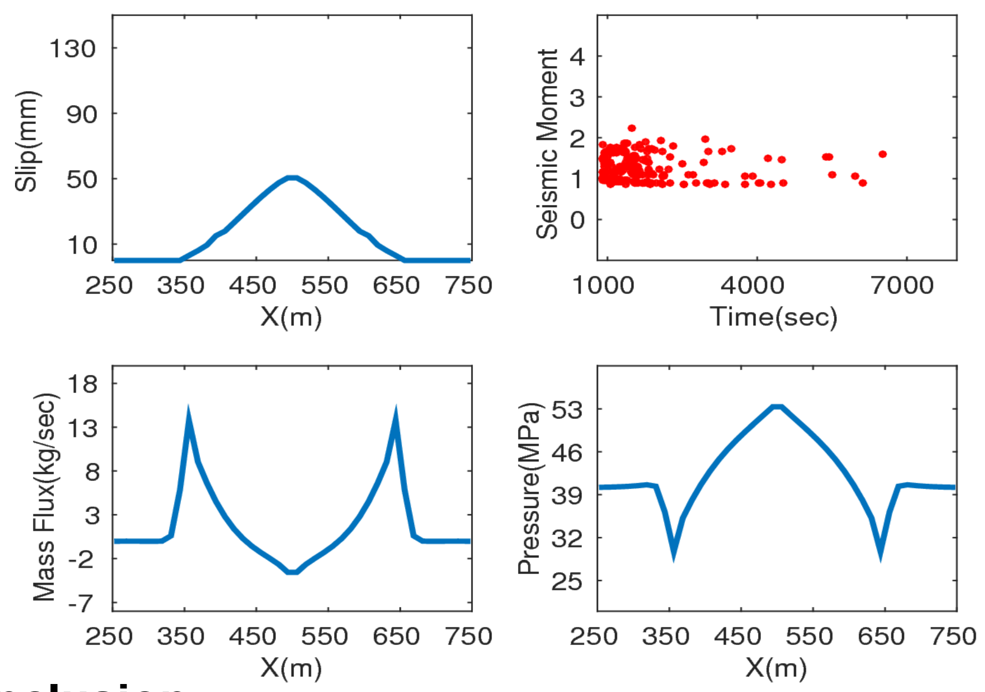
$$\frac{\partial E^i_f}{\partial t} = \frac{(E^i_* - E^i_f)}{\tau^t} \quad (7)$$

Results

A constant pressure injection into a single fracture surrounded by a porous matrix is simulated for both flow and shear failure.



The pressure contour of the matrix just after a shear failure incident depicts a drop in matrix pressure in the region surrounding the fracture failure and a subsequent mass flow from matrix to fracture during the flow relaxation period. The following figure shows the result of total slip, seismic moment magnitude, matrix to fracture mass flux and the pressure profile along the fracture.



Conclusion

The developed volume relaxation model, stabilizes the flow solver without resolving the timescale of mechanical shear failure. As a result of this, a pressure diffusion dominiated shear failure is observed along the fracture.

References

1. Hajibeygi, H., Karvounis, D. & Jenny, P. 2011: *Journal of Computational Physics 230, 8729-8743.*

2. McClure, M. & Horne, R. 2011: *Geophysics 76, 6, 181-198*