Integrated approach to induced seismicity modeling

C. Meng (cmeng@mit.edu) B. Hager

ERL, MIT

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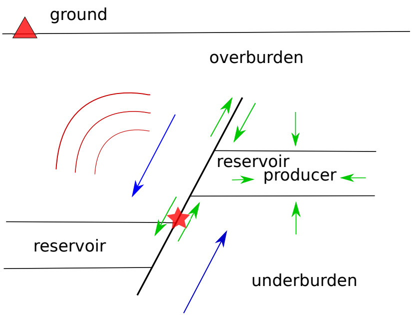
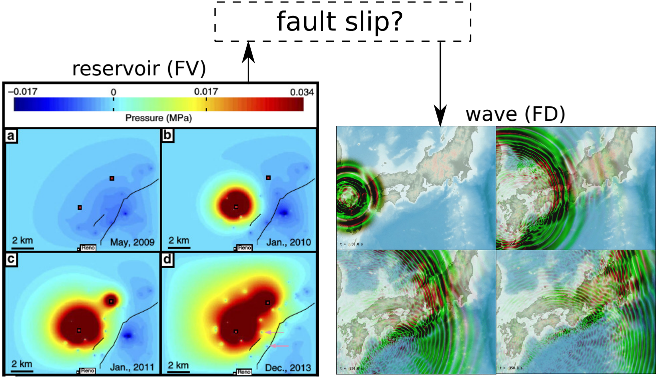
Reservoir production/injection induced seismicity



A numerical model that correlates reservoir injection/production scenarios with seismicity:

- Fluid injection/withdrawal perturbs initial fault traction.
- Fault slip is triggered when certain condition is met.
- Seismic motion is felt at surface.

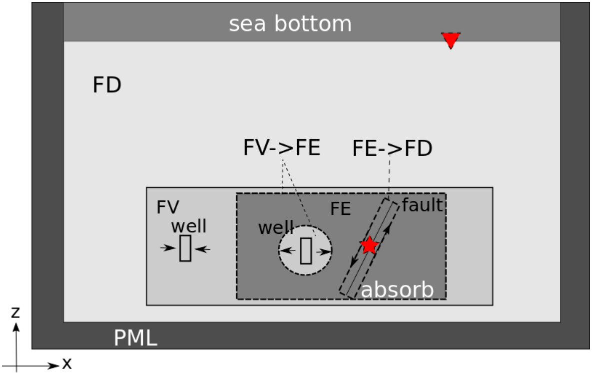
Disconnect between reservoir and ground motion models



- Spatially and temporally, reservoir and earthquake models overlap but belong to different scales.
- Physically, these two models have no obvious overlaps.
- fortunately, the region affected by induced earthquakes is about 20 $\times$ 20 km.

"One-click" model from fluid injection/production to ground motion

- FV and FE pressures are synced at boundary and well regions.
- FE and FD rupture motions are synced around slipping fault.
- FE runs at (quasi-)static and dynamic time steps to sync with FV and FD respectively.



Assumptions

The finite volume (Pflotran) model,

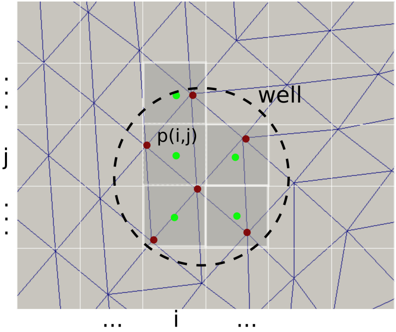
- is adequate for well region pressure.
- is adequate for full domain phase invading/replacement and resulting transient permeability.
- is not able to capture porelastic rebound due to fault rupture.

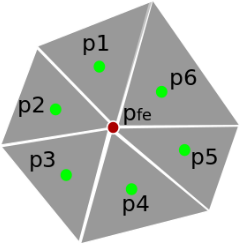
The fault rupture,

- is not affected by the reflections from ground surface.
- will not alter fluid and matrix properties, e.g. permeability.

Spatial interpolation

- From structured FV model, FE (nodal) pressure is sampled from the containing cells.
- From unstructured FV model, FE pressure is sampled from neighboring cells by spatial integration and normalization.





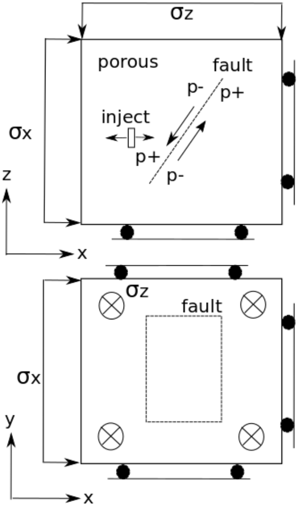
Imposing pressure in FE solution space

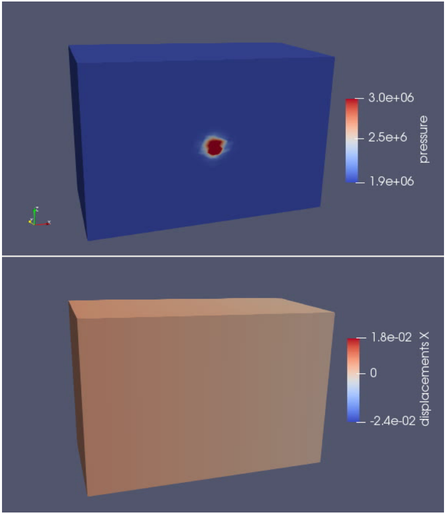
Poroelastic equation: $\mathbf{KU} = \mathbf{F}$,

where $\mathbf{K} = \begin{bmatrix} \mathbf{K}_e & \mathbf{H} \\ -\mathbf{H}^T & \Delta t \mathbf{K}_c + \mathbf{S}_p \end{bmatrix}$, $\mathbf{U} = \begin{bmatrix} \mathbf{u} \\ \mathbf{p} \end{bmatrix}$, $\mathbf{F} = \begin{bmatrix} \mathbf{f} - \mathbf{H}\mathbf{p}^{\text{sync}} \\ \mathbf{Q} - \Delta t \mathbf{K}_c \mathbf{p} \end{bmatrix}$.

- Locate coefficients of the synced pressures in matrix $\mathbf{K}$, and zero out other entries sharing the same rows or columns.
- Locate entries of the synced pressure in RHS, and replace them by $\mathbf{p}^{\text{sync}}$ multiplied by their corresponding coefficients in $\mathbf{K}$.
- Multiply matrix $\mathbf{H}$ with synced pressure space $\mathbf{p}^{\text{sync}}$ (unsynced parts take zero), and subtract it from the $\mathbf{f}$ of RHS.
- Modify the domain permeability contained by $\mathbf{K}_c$. If the FV model is multiphase, sync permeability for every time step.

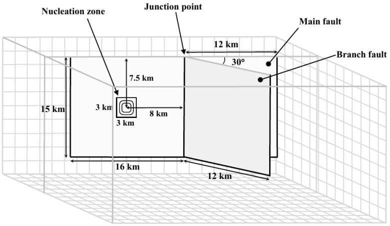
Injection induced fault slip

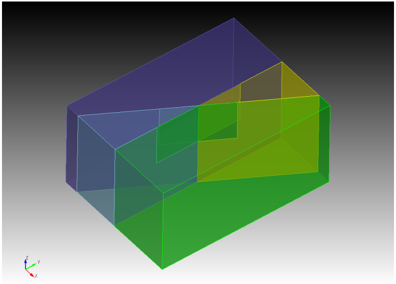




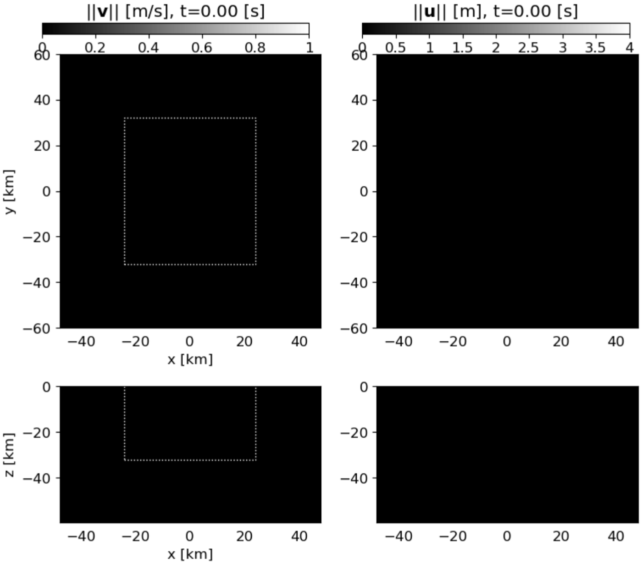
Intersecting fault problem (modified from SCEC14/15)

- SCEC14 and 15 avoid intersection by terminating split nodes.
- Modified models allow fault intersection.

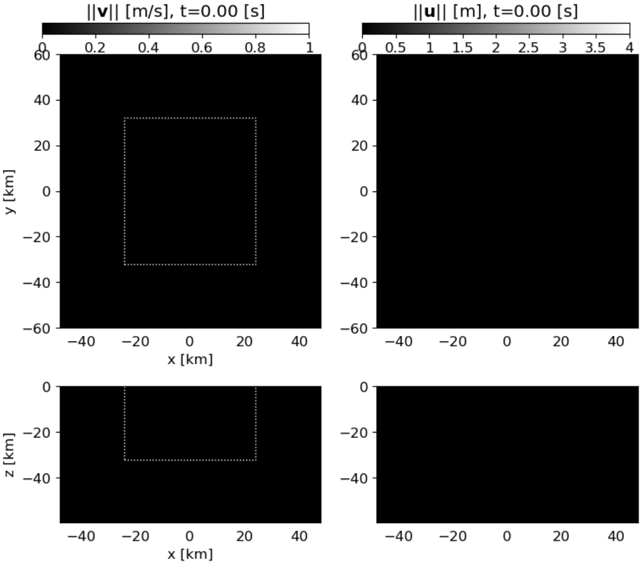


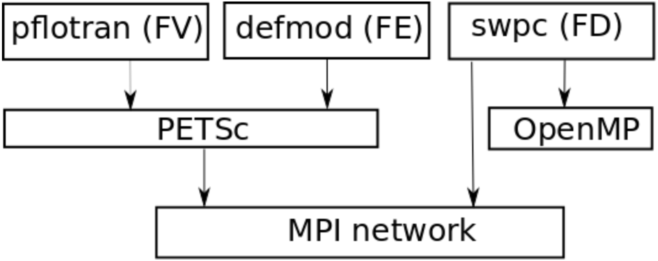


Modified SCEC14: Main fault truncating secondary fault



Modified SCEC15: Secondary fault truncating main fault





- Parallel run from end to end.
- FV and FE modules share the same linear algebra (PETSc) framework which can scale up to ∼2 billion unknowns.
- FD module, with distributed and shared (MPI+OpenMPI) hybrid parallelization, can scale up to ∼1 trillion unknowns.

Summary:

- A single numerical method is difficult to satisfy the requirement for modeling induced seismicity.
- Finite volume, finite element and finite difference models are connected to form a “one-click” approach.
- This approach allows one to directly correlate injection/production scenarios with seismic ground motions.

For source code and above examples, visit `https://github.com/Chunfang/defmod-swpc`.

Comparisons

- High order explicit FE methods (SEM, DG) suffer strict CFL condition, and do not solve (quasi-)static equations.
- Linear FE can solve both the static and dynamic equations, but suffers strict CFL condition, i.e. expensive for field scale ground motions.

	this	Pylith	SPECFEM	Seissol	Comsol
method	FE-FD	FE	SEM	DG	FE
static	✓	✓			✓
dynamic	✓	✓	✓	✓	✓
both	✓				?
poroelastic	✓		?		✓
open	✓	✓	✓	✓	

Benchmarks

functionality	method	benchmark
poroelasticity	implicit, pore pressure stabilization	Mandel
viscoelastic power law	implicit	Abaqus, Relax
fault, rupture, FE-FD binding	implicit/explicit Lagrange Multiplier	Mohr-Coulomb, SCEC