Towards Extreme-Scale Multiphysics Simulations for Induced Earthquakes

PASC22

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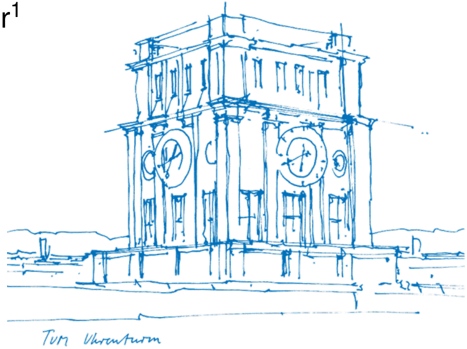


Induced Earthquakes

- Earthquakes caused by human activity
- Mining, geothermal energy production, carbon capture and storage, oil/gas extraction
- 1239 induced earthquakes in the HiQuake database[1].
- Examples
  - Pohang 2017: M5.5 (Palgunadi et al. 2020)
  - Otaniemi 2018: $<$ M2 (Hillers et al. 2020)

In order to understand these earthquakes better: Numerical simulations with SeisSol

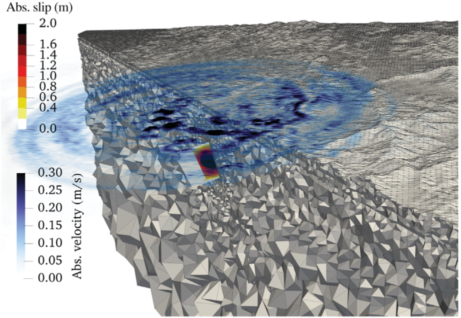
[1] Wilson et al. 2017: `https://inducedearthquakes.org/`, accessed 23rd June, 2022

Earthquake simulations

Solve the elastic wave equation:

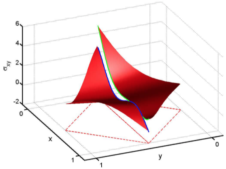
- $\partial_t q + A\partial_x q + B\partial_y q + C\partial_z q = 0$
- q contains stresses and velocities, A, B and C contain material information.

Figure: (Palgunadi et al. 2020): "Dynamic Fault Interaction during a Fluid-Injection-Induced Earthquake: The 2017 Mw 5.5 Pohang Event"



SeisSol: ADER-DG for Earthquake simulations

Discontinuous Galerkin method with Arbitrary DERivatives time-stepping: ADER-DG: Achieve the same high order in space *and* time



SeisSol specific:

- Tetrahedral elements
- Modal (orthogonal) basis functions: Diagonal mass matrix, upper triangular stiffness matrix
- Exact Riemann solver for the numerical flux between elements

HPC optimizations

Parallelization

- Element local discretization with DG
- Mesh partitioning based on workload estimate
- Exchange values at partition boundaries

Node-level performance

- Update scheme is a sequence of tensor contractions.
- Use code generator `YATeTo` [2] to map the tensor operations to GEMMs ($C = \alpha AB + \beta C$).
- Use architecture specific backends for optimized code.

[2] (Uphoff and Bader 2020)

Strong Scaling

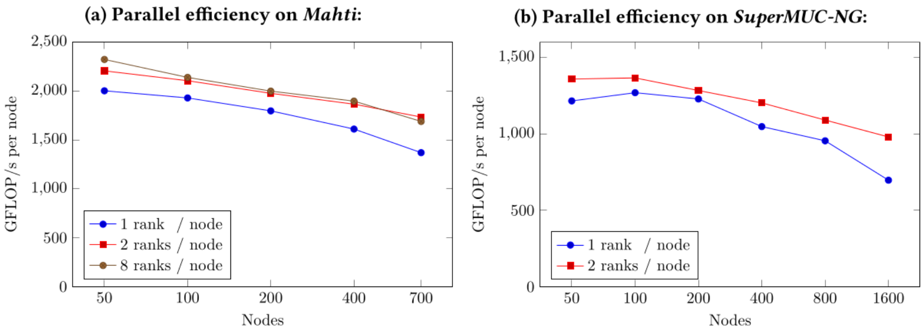


Figure: Strong scaling on recent supercomputers. Image taken from (Krenz, Uphoff, et al. 2021).

Anisotropic materials

- Directional dependent material behaviour, e.g. cracked or layered media
- Jacobian A, B, C are more densely populated, but can reuse the numerical scheme from the elastic wave equation (Wolf, Gabriel, and Bader 2020)

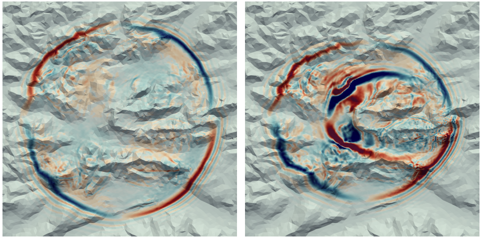


Figure: Left: isotropic material, Right: anisotropic material

Isotropic:

$$\sigma = \lambda \mathrm{tr}(\epsilon) I + 2\mu\epsilon$$

Anisotropic:

$$\sigma_{ij} = \sum_{k,l=1}^{3} c_{ijkl}\epsilon_{kl}$$

Poroelastic materials

- Interaction of fluid and solid phase introduces a stiff source term to the wave equation
- Replace Cauchy-Kowalevski procedure with space-time variant of ADER-DG
- Use sparsity pattern of the system matrix to efficiently solve the linear system (Wolf, Galis, et al. 2022)

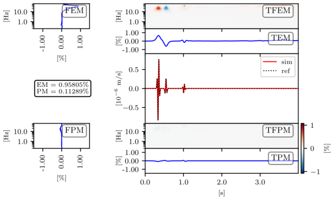


Figure: Double couple source in a poroelastic medium

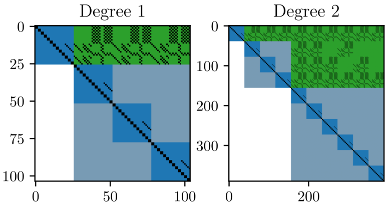
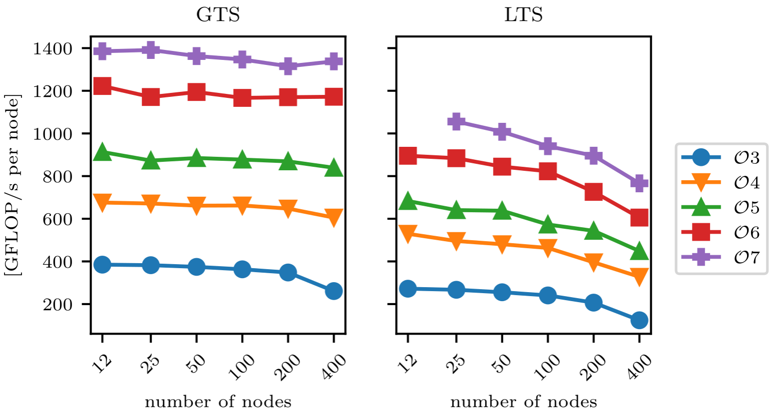


Figure: Sparsity patterns for the space-time ADER-DG variant

Scalability

Figure: Parallel efficiency of a poroelastic setup with 7.3 million elements for global (GTS) and local (LTS) time-stepping on SuperMUC-NG.



Kinematic earthquake sources

- Prescribe slip at a several points or along the complete fault fault.
- Watch how waves propagate through the medium.
- No information about what happens at the fault
- No interaction between wavefield and fault.

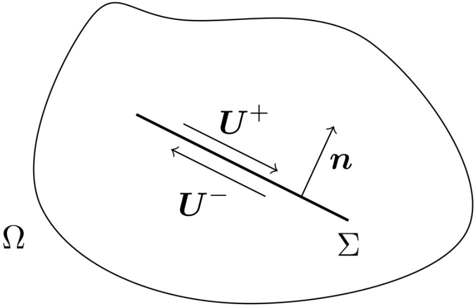


Figure: Sketch of an earthquake source along a fault. Image taken from (Uphoff 2020)

Dynamic rupture earthquake sources

- Instead of numerical fluxes: Solve a friction problem at (selected) element interfaces.
- Interaction between wave propagation and source dynamics
- Gives insight into the rupture process
- Up to now dynamic rupture works only with (visco-)elastic materials.

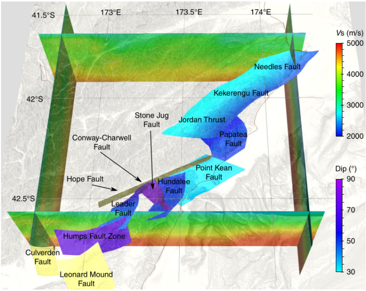


Figure: Complicated fault network, image taken from (Ulrich et al. 2019).

Combine all the Multiphysics

Elasticity + Pore Fluids + Friction Problem

How does Dynamic Rupture work in elastic media

<u>Elasticity</u> + **Pore Fluids** + **<u>Friction Problem</u>**

1. Solve the Riemann problem to get states at the interface.
2. Compute fault strength τ_S based on the friction law.
3. Find shear traction **t** and slip rate **s** such that $\tau_S \mathbf{s} = \mathbf{t}\|\mathbf{s}\|$.
4. Impose state with **s** and **t** at the interface.

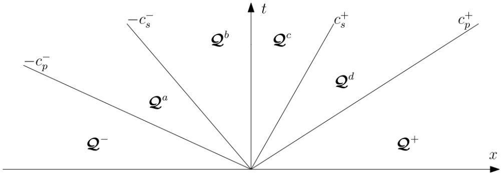


Figure: Solution structure of the elastic Riemann problem

What do we need to change for poroelastic media

Elasticity + **Pore Fluids** + **Friction Problem**

1. Fluid pressure now affects solution of the Riemann problem.
2. Fault strength depends on the pressure (and temperature)[3].
3. Find shear traction **t** and slip rate **s**, but what about relative fluid velocity?

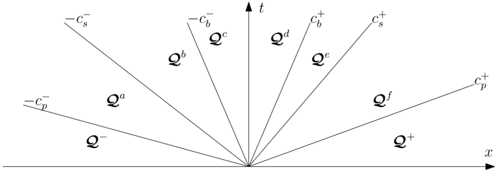


Figure: Solution structure of the poroelastic Riemann problem

[3](Noda and Lapusta 2010)

How to verify the results?

- Hard to find analytic solutions for combined friction and wave propagation problem.
- Community effort through SCEC to compare different dynamic rupture codes.

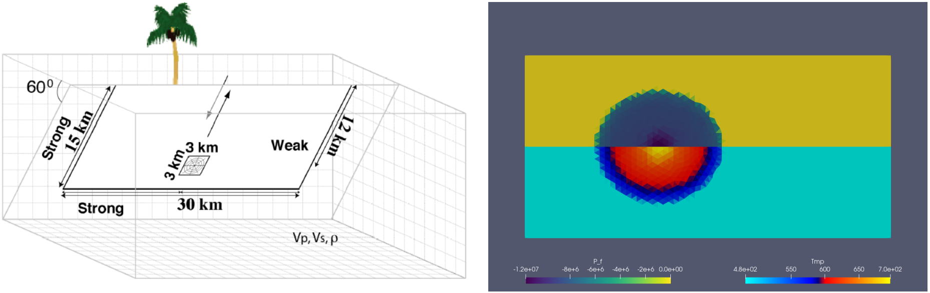


Figure: Left: Geometry of the SCEC benchmark TPV12. Image taken from (Harris et al. 2009). Right: Results of the TPV105 benchmark (top: pressure, bottom: temperature).

Conclusion

- Extended SeisSol's functionality to incorporate more complicated material models.
- Work in progress: Dynamic Rupture in poroelastic materials.
- Upcoming work: Compute, compute, compute

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Quantify poroelastic effects relevant for wave propagation

- Compare poroelastic materials with their elastic equivalents
- Study the Utsira sandstone formation used for CCS[4]
- Energy dissipation at material interfaces.

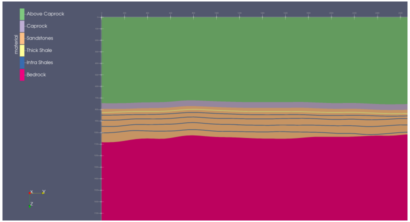
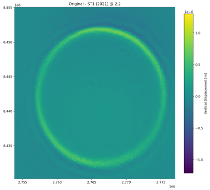


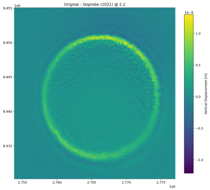
Figure: Cut through the layered Utsira model.

[4] Equinor 2022

Nuisance patterns from the stimulation of Enhanced Geothermal systems

- Geothermal Energy production near Helsinki: Neighbors reported sound disturbance connected to induced earthquakes.
- We used the elastic-acoustic coupling feature of SeisSol to simulate which sounds an earthquake emits.
- Parameter study: How does the source mechanism and the geological subsurface structure influence the nuisance pattern? (Krenz, Wolf, et al. 2022).





Backup Slide Equations

Weak formulation of the PDE in 1D:

$$\int_T \partial_t q \cdot \phi \mathrm{d}x - \int_T Aq\partial_x \phi \mathrm{d}x + \int_{\partial T} \phi Aq \cdot n \mathrm{d}s = \int_T Eq\phi \mathrm{d}x$$

Semidiscrete form:

$$\partial_t Q_{pl} \int_T \phi_l \phi_k \mathrm{d}x - A_{pq} Q_{pl} \int_T \phi_l \partial_x \phi_k \mathrm{d}x$$
$$+ \int_{\partial T} F_{pk}(Q_{pl}, Q^i_{pl}) \mathrm{d}s$$
$$= E_{pq} Q_{pl} \int_T \phi_l \phi_k \mathrm{d}x$$