Coupled elastic-acoustic simulations

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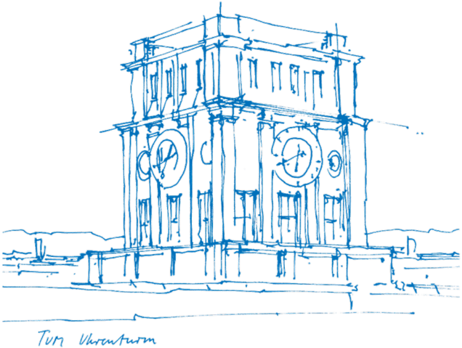
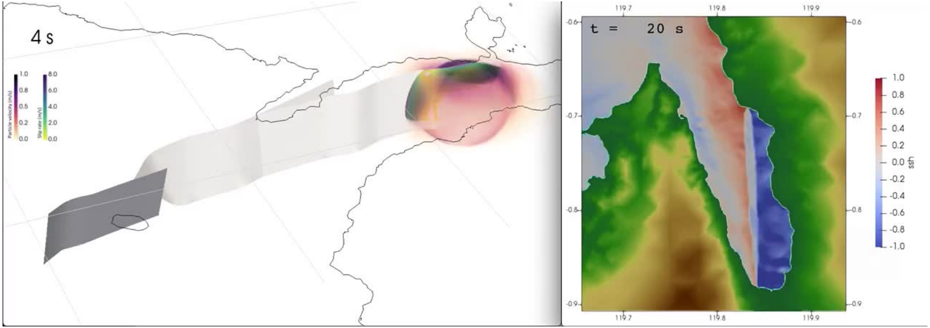


Earthquake-Tsunami Coupling

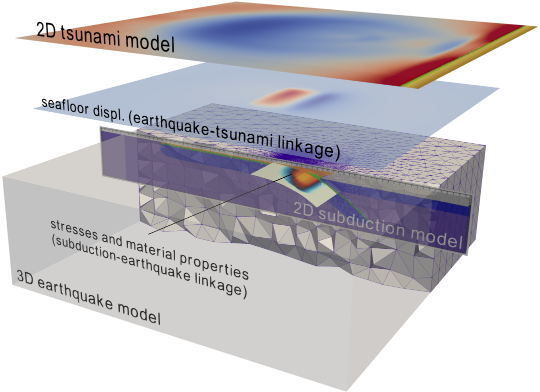


Palu earthquake/tsunami[1], left: earthquake, right: tsunami

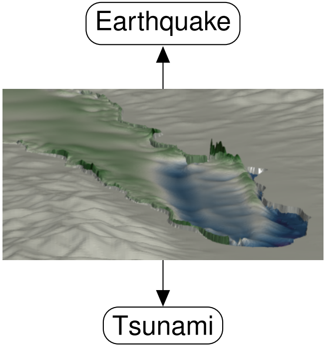
[1] T. Ulrich et al. "Coupled, Physics-based Modelling Reveals Earthquake Displacements are Critical to the 2018 Palu, Sulawesi Tsunami". In: *Pure and Applied Geophysics* (2019).

Earthquake-Tsunami Coupling Workflows

One-way Linking[2]



Fully Coupled



[2] E. H. Madden et al. “Linked 3-D modelling of megathrust earthquake-tsunami events: from subduction to tsunami run up”. In: *Geophysical Journal International* 224.1 (2021)

One-way linking vs 3D coupling

Using shallow water equations for tsunami has disadvantages:

- No dispersion (if not using Boussinesq approximation)
- No acoustic waves (i.e. assuming incompressible ocean)
- Only works in shallow water limit

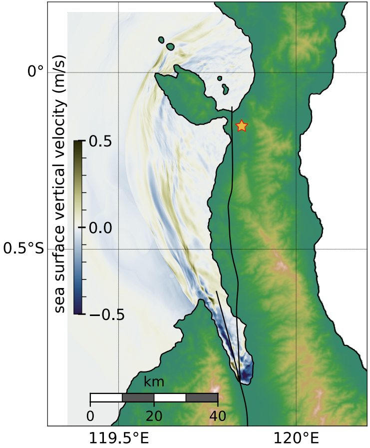
Fully-coupled elastic-acoustic model solves entirely new class of earthquake-tsunami problem
Compares well with one-way linking in sufficiently shallow water
Seismic and acoustic waves can be dominant in data recorded by offshore instruments.

Detailed model comparison work in progress[3]

[3] L. S. Abrahams et al. "Comparison of techniques for coupled earthquake and tsunami modeling". In: *AGU Fall Meeting Abstracts* (2020).

Example: Palu, Sulawesi September 2018

- $M_w 7.5$ strike-slip earthquake
- Propagation at supershear speed crossing narrow Palu Bay
- Followed by unexpected and localized tsunami
- Complicated geometry: bath-tub like bay, very shallow water (average 600 m)
- Details: L. Krenz et al. "3D Acoustic-Elastic Coupling with Gravity: The Dynamics of the 2018 Palu, Sulawesi Earthquake and Tsunami". In: *Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis*. St. Louis Missouri, Nov. 2021.



Modeling Goals & Resulting Challenges

Goals

- Capture entire process: earthquake rupture, generation and propagation of seismic waves, ocean acoustic waves and tsunamis
- High resolution in 3D Earth (10 Hz) and ocean (15 Hz)
- Complex geometry, including bathymetry/topography
- **3D** solid-fluid coupling

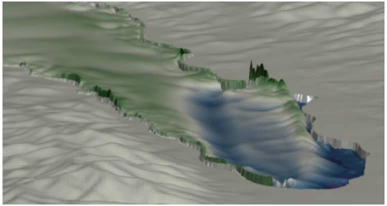
Challenges

- Resolution leads to large setups: $\approx$ 250 billion degrees of freedom
- Vastly different element sizes $\implies$ vastly different time step size
- Geometry requires unstructured meshes

SeisSol

What

- (An)**Isotropic elastic** seismic wave propagation
- **Acoustic** wave propagation
- Viscoelastic wave propagation
- Poroelasticity
- **Off-fault plasticity**
- **Dynamic earthquake rupture**



How

- Numerics: ADER-DG
- Unstructured tetrahedral meshes with local time-stepping
- Optimized Hybrid MPI + OpenMP Parallelization

Available (**open-source**) at `https://github.com/SeisSol/SeisSol/`.

The ADER-DG Approach[4]

Solve linear hyperbolic equations of the form

$$\frac{\partial \boldsymbol{q}}{\partial t} + \boldsymbol{A}\frac{\partial \boldsymbol{q}}{\partial x} + \boldsymbol{B}\frac{\partial \boldsymbol{q}}{\partial y} + \boldsymbol{C}\frac{\partial \boldsymbol{q}}{\partial z} = 0 \tag{1}$$

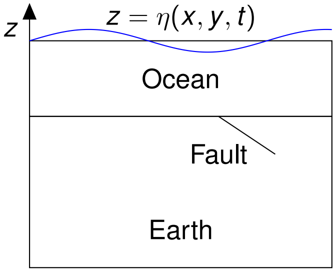
with $\boldsymbol{q}$ vector of variables, $\boldsymbol{x} = (x, y, z)$ position, t time, $\boldsymbol{A}(\boldsymbol{x}), \boldsymbol{B}(\boldsymbol{x}), \boldsymbol{C}(\boldsymbol{x})$ flux matrices.

Discontinuous Galerkin (DG) divides domain into disjoint elements, approximates solutions by **piecewise-polynomials**.
Elements are connected by solving the **Riemann** problem **exactly**.

ADER-Approach uses **element-local Taylor expansion** for time integration instead of Runge-Kutta procedures.
Advantages: **One-step scheme**, **arbitrary order in time and space**

[4] V. A. Titarev and E. F. Toro. “ADER: Arbitrary High Order Godunov Approach”. In: *Journal of Scientific Computing* 17.1 (Dec. 2002).

Two-Way Elastic-Acoustic Coupling



Based on 2D model of Lotto and Dunham[5]
Here: First 3D implementation!

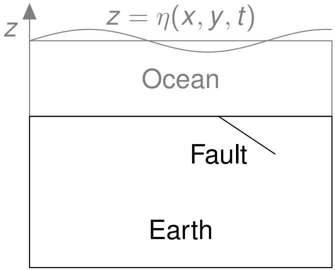
With:

- $\eta(x, y, t)$ sea surface height
- Ocean at rest at $z = 0$

Figures in 2D for illustration, all simulations are **3D**

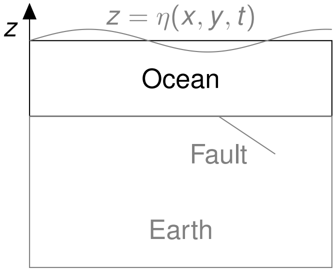
[5] G. C. Lotto and E. M. Dunham. "High-order finite difference modeling of tsunami generation in a compressible ocean from offshore earthquakes". In: *Computational Geosciences* 19.2 (2015)

Earth Model



- Isotropic elastic medium
- Velocity-stress formulation
- $\boldsymbol{q} = (u, v, w, \boldsymbol{\sigma})$
- u, v, w velocities
- $\boldsymbol{\sigma}$ stress tensor
- ρ density, (μ, λ) Lamé parameters
- Dynamic rupture earthquake source (here: fast velocity weakening rate-and-state friction)

Ocean Model[6]



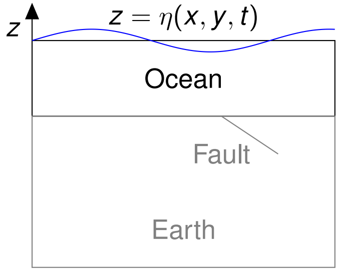
Modeled as **linear acoustic** medium, $\boldsymbol{q} = (u, v, w, p)$
Treated as special case of elastic wave equation with $\mu = 0$ and $\sigma_{ij} = -p\delta_{ij}$.
Pressure p sum of background pressure p_0 (in **hydrostatic equilibrium**) and perturbation p'.

$$\begin{aligned} p &= p_0 + p'(x, y, z) \\ p_0 &= p_a + \rho g(-z) \end{aligned} \tag{2}$$

with atmospheric pressure p_a and $g = 9.81\,\mathrm{m/s^2}$.

[6] G. C. Lotto and E. M. Dunham. "High-order finite difference modeling of tsunami generation in a compressible ocean from offshore earthquakes". In: *Computational Geosciences* 19.2 (2015).

Ocean Model: Free Surface



Physical free surface boundary condition at sea surface height η:

$$p(x, y, \eta) = 0 \tag{3}$$

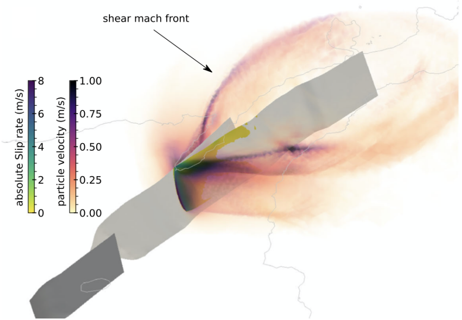
Typically solved by moving mesh.
Expensive, instead use **linearization** and **hydrostatic background pressure**:

$$\begin{aligned} p(x, y, z = 0) &= \rho g \eta(x, y) \\ \frac{\partial \eta}{\partial t} &= w \end{aligned} \tag{4}$$

Important to use w at boundary (solution of Riemann problem), otherwise unstable!
Solve equation (4) with ODE solver

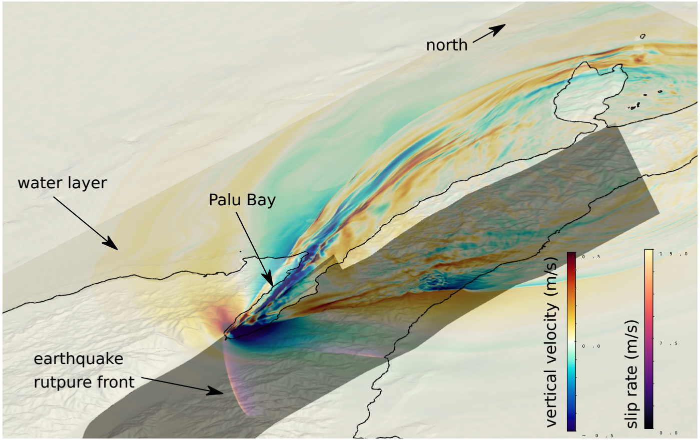
Palu: Our setup

- Added water layer to existing earthquake model[7].
- Fully coupled model (including plasticity, dynamic earthquake rupture)
- Two meshes: **M** (89 million elements), **L** (518 million elements)
- Poly. Order 5, 46 and 261 billion degrees of freedom
- **M** took 5.3 hours on 1000 nodes of SuperMUC-NG for 100s simulated time
- **L** took 5.5 hours on 3072 nodes of SuperMUC-NG for 30s simulated time



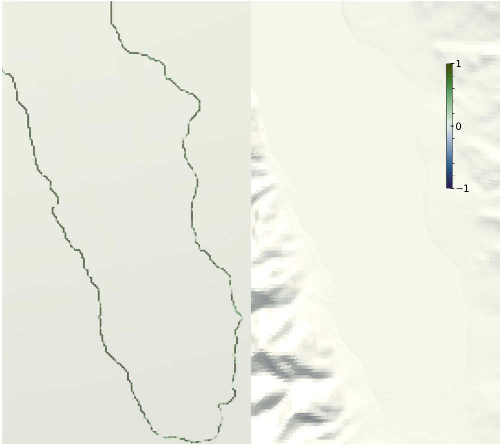
[7] T. Ulrich et al. "Coupled, Physics-based Modelling Reveals Earthquake Displacements are Critical to the 2018 Palu, Sulawesi Tsunami". In: *Pure and Applied Geophysics* (2019)

Palu: 3D View at 15s



Slip rate (on faults), vertical sea-surface/Earth velocity at 15 s

Comparison with One-Way Linking



Left: One-way linking, **Right: fully-coupled**

Otaniemi EGS-Induced Earthquake

- Otaniemi project
- Enhanced geothermal system (EGS), stimulated in June and July 2018 in the region of Helsinki
- Thousands of induced earthquakes
- No event exceeded threshold magnitude
- However: Observations of ground shaking and audible disturbances collected by Macroseismic questionnaire of the Institute of Seismology, University of Helsinki[8]

Goal: create "discomfort maps"
See also: talk at next week's EGU (Monday):
L. Krenz et al. "The variability of seismo-acoustic nuisance patterns: a case study from the Helsinki geothermal stimulation". In: *EGU General Assembly* (2022)

[8] G. Hillers et al. "The 2018 Geothermal Reservoir Stimulation in Espoo/Helsinki, Southern Finland: Seismic Network Anatomy and Data Features". In: *Seismological Research Letters* 91.2A (Feb. 2020).

Fully-coupled model

- Kinematic point source
- Geometry with realistic topography but ignore shallow Helsinki bay Laajalahti
- Earth modeled by elastic wave equation, air by acoustic wave equation
- Analytical methods not sufficient, need numerical approach
- Compute loudness as

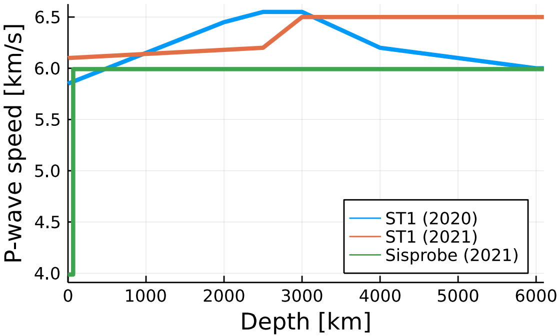
  $$20 \log_{10} \left(\frac{p^{\text{peak}}}{p^{\text{ref}}} \right) dB$$

  with measured peak pressure p^{peak} and reference pressure p^{ref}
- Humans perceive sounds with different loudness, depending on frequency
- Use weighting factors (via digital filtering) to get loudness from volume
- We need to resolve at least 20Hz, better up to 50Hz.

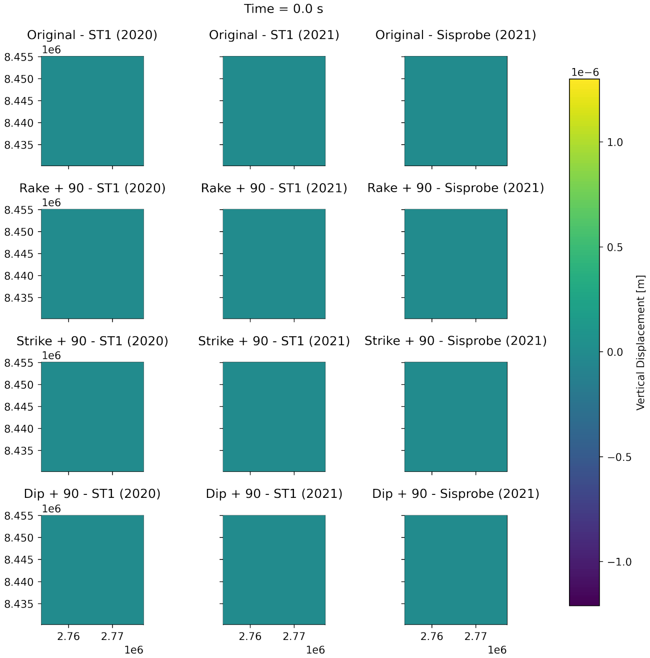
Velocity Models

Currently comparing three models

- ST1 (2019)[9]
- ST1 (2021),[10]
- Sisprobe, full inversion (currently simplified 1D version)[11]

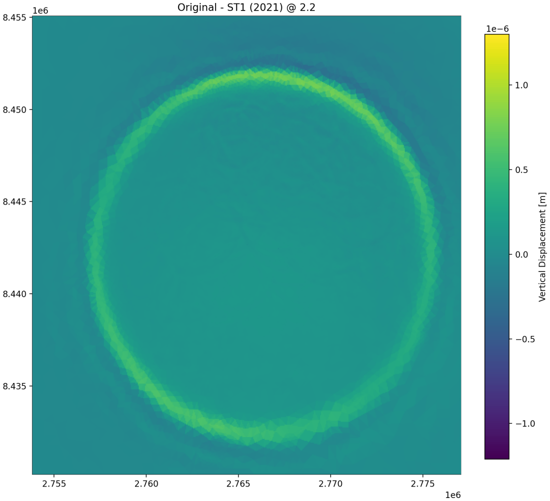


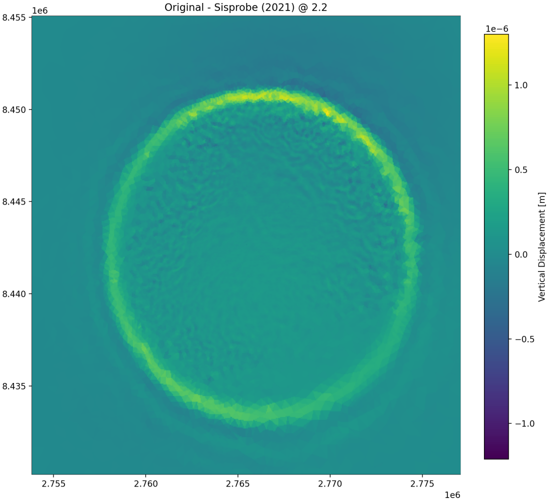
[2] G. Kwiatek et al. "Controlling fluid-induced seismicity during a 6.1-km-deep geothermal stimulation in Finland". In: *Science Advances* 5.5 (2019)
[3] M. Leonhardt et al. "Seismicity during and after stimulation of a 6.1 km deep enhanced geothermal system in Helsinki, Finland". In: *Solid Earth* 12.3 (Mar. 2021)
[4] Roméo Courbis, Sisprobe



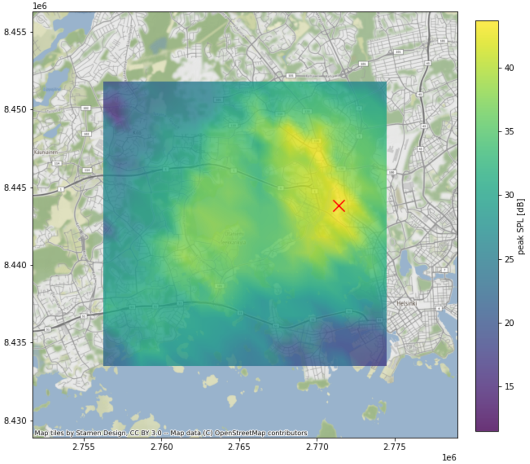
- Case study:
- Source mechanisms
- Velocity models
- “what if?”

Velocity Model Comparison





Discomfort Map



- Result: Map that shows areas with large sound pressure
- Sound recorded at 0.5 m height
- Note: Without frequency weighting

Conclusion

- Fully coupled elastic-acoustic simulations capture more effects than typical one-way linking strategies
- Linearization of free surface boundary conditions efficient way of tracking sea surface height
- Pronounced differences in Palu scenario: “smoother” tsunami
- It can also be used for generation of “discomfort maps”, as Otaniemi example showed

ChEESE

Center of Excellence for Exascale in Solid Earth

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