Elastic-acoustic coupling for large scale earthquake simulations

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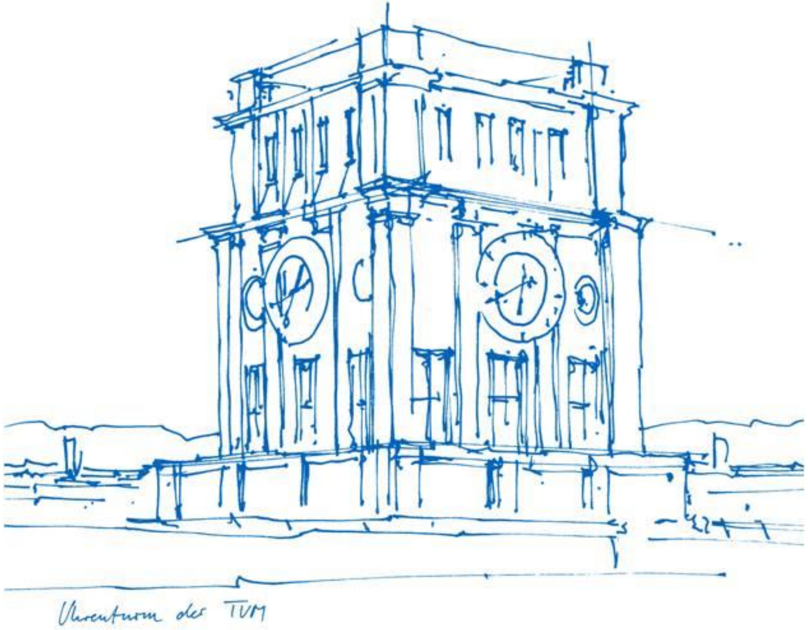

Collaborations & Funding

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Earthquake-Tsunami Coupling Workflows

One-way Linked

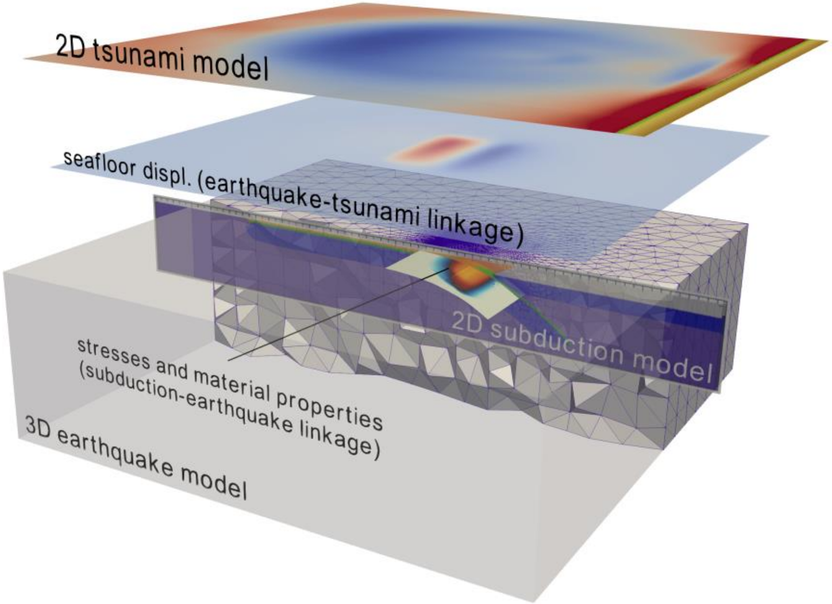

Figure from: H. Madden et al. "Linked 3-D modelling of megathrust earthquake-tsunami events: from subduction to tsunami run up (2021)

Fully Coupled

Earthquake

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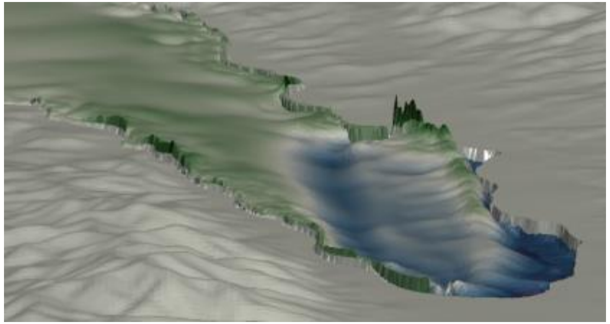

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Tsunami

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) -> **Potentially dominant** in data recorded by offshore instruments
- Only works in **shallow water** limit

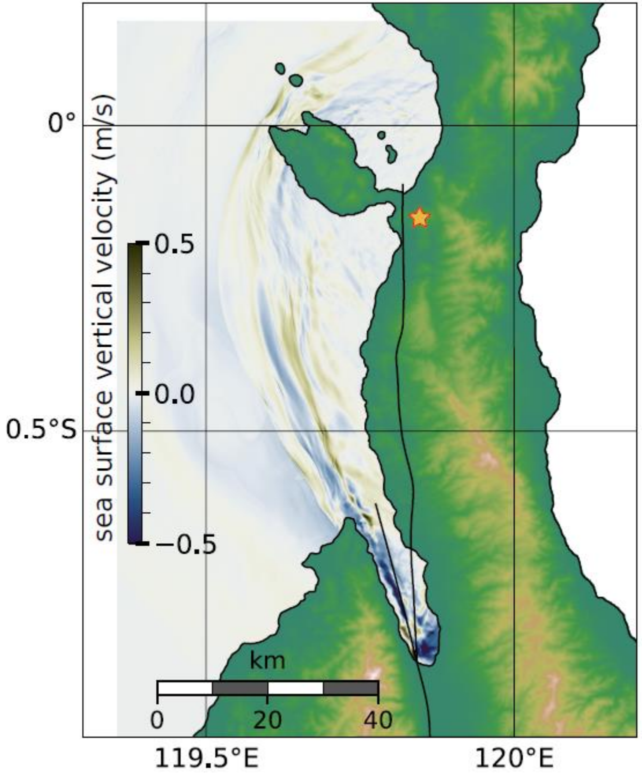
Fully-coupled elastic-acoustic model solves **entirely new class** of earthquake-tsunami problem

Compares well with one-way linking under certain conditions

Detailed model comparison: Abrahams, Lauren S., et al. "Comparison of methods for coupled earthquake and tsunami modelling." *Geophysical Journal International* 234.1 (2023)

Example: Palu, Sulawesi September 2018

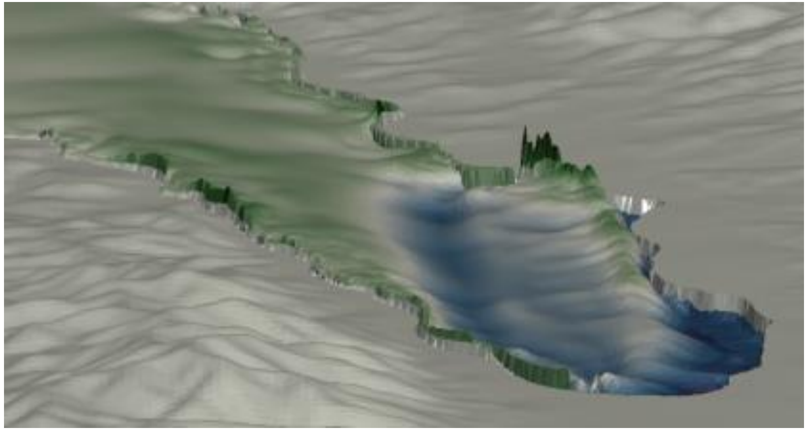
- Mw 7.5 **strike-slip** earthquake
  Propagation at **supershear** speed crossing narrow Palu Bay
- Followed by **unexpected** and **localized tsunami**
- Complicated geometry: bath-tub like bay, very shallow water (average 600 m)
- Details: L. Krenz et al. “3D Acoustic-Elastic Coupling with Gravity: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



SeisSol

What

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

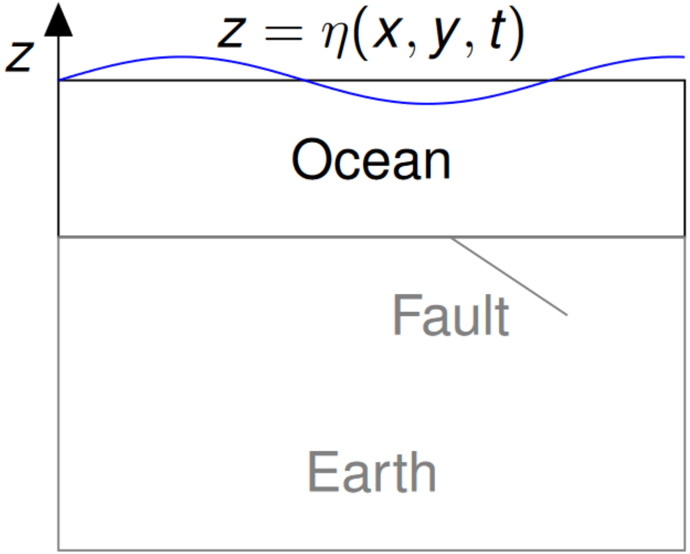


How

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

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

Ocean Model



Linear acoustic medium, q = (u, v , w, p)

Treated as special case of elastic wave equation with stress tensor $\sigma_{ij} = -p\ \delta_{ij}$,density ρ and $g = 9.81\frac{m}{s^2}$.

Free surface

$$p(x, y, \eta) = 0$$

Typically solved by moving mesh.

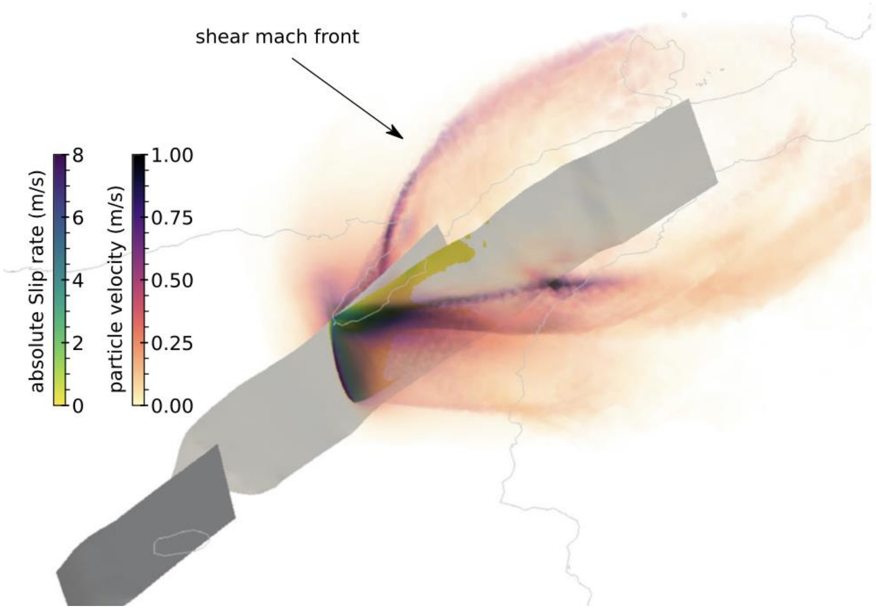
Following (Lotto, Dunham 2015),linearized to:

$$p(x, y, z = 0) = \rho g\ \eta(x, y)$$

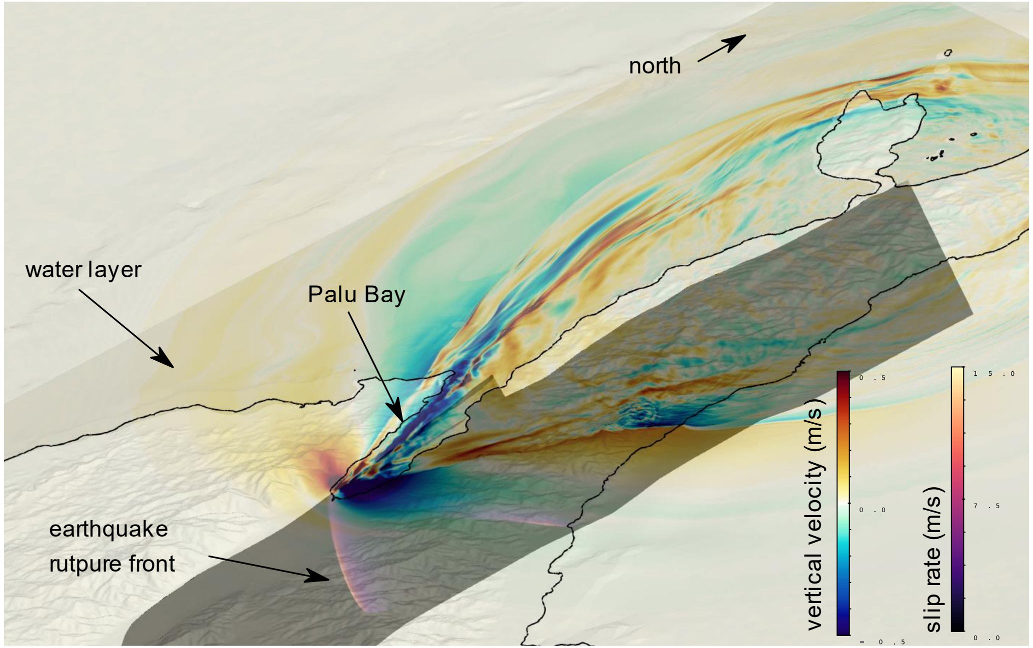
$$\frac{\partial \eta}{\partial t} = v_z$$

Palu: Our setup

- Added **water layer** to existing earthquake model (Ulrich et al., 2019).
- **Fully coupled** model (including plasticity,seismic and acoustic waves, dynamic,earthquake rupture)
- Two meshes: **M** (89 million elements), **L** (518 million elements)
- **Poly. Order 5**, 46 and 261 billion degrees of freedom
- M: 5.3 hours on **1000 nodes** of SuperMUC-NG for 100s simulated time
- L: 5.5 hours on **3072 nodes** of SuperMUC-NG for 30s simulated time



Palu: 3D View at 15s



Comparison with One-Way Linking

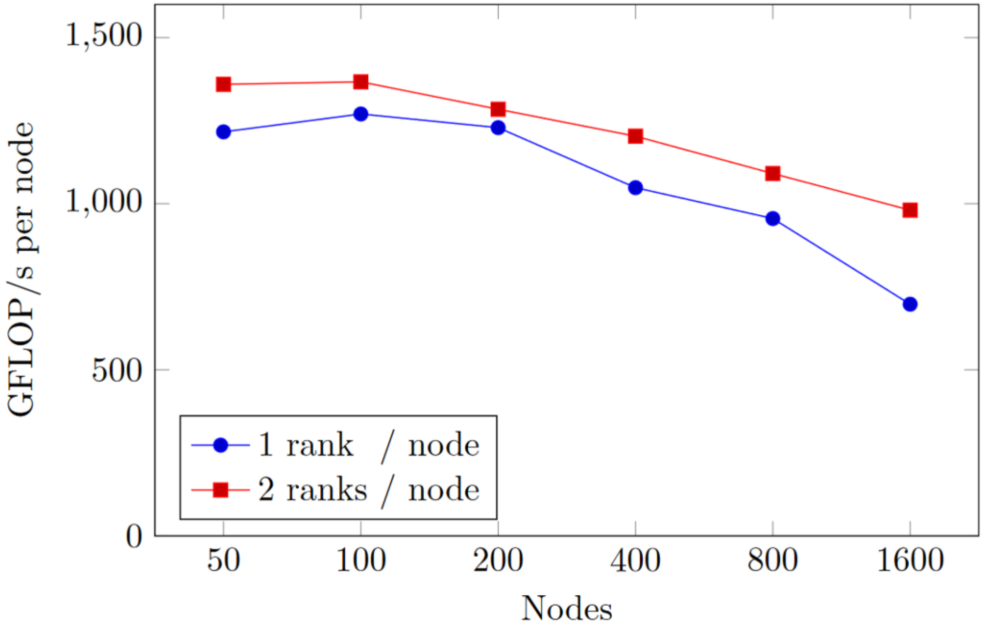
Left: One-way linking, **right: fully-coupled**

Shows: Sea surface displacement for $t = 1s, \dots, 100s$

Use identical earthquake model

Matches well overall, with some differences (e.g. at coast, “smoother” tsunami)

Strong Scaling on SuperMUC-NG

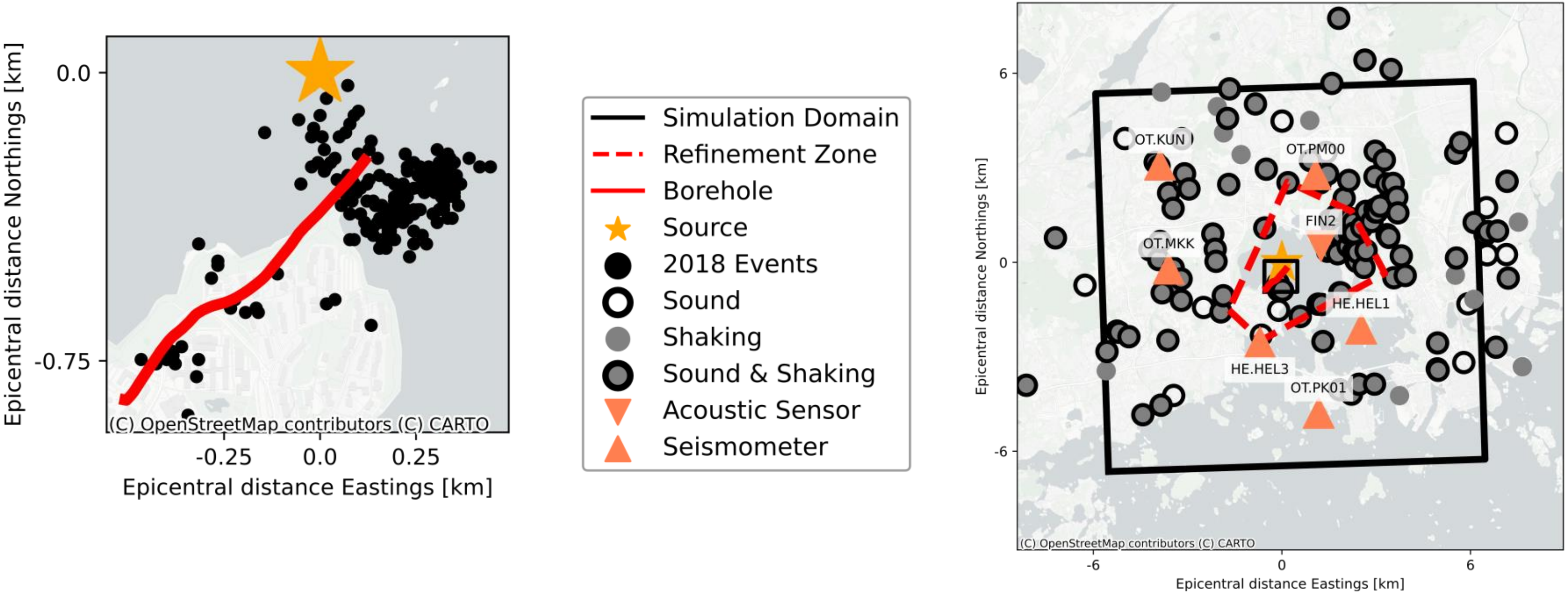


“Big blast followed by a long 10-second echo.” Helsinki, 2018-07-08 20:37

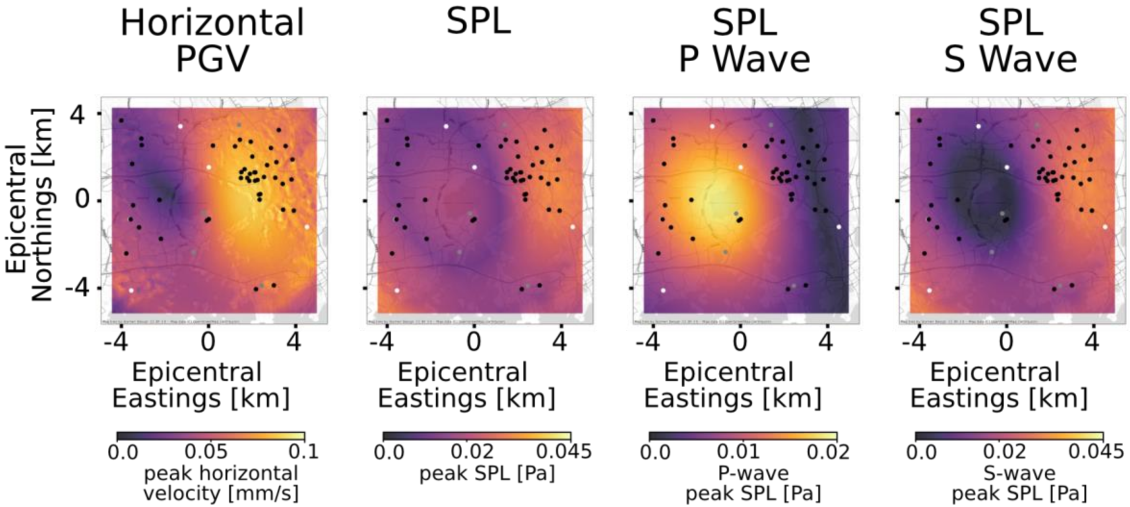
Enhanced Geothermal System in Helsinki

- Otaniemi project
- Enhanced geothermal system (EGS), stimulated in June and July 2018 in the region of Helsinki
- Thousands of **induced, small earthquakes**
- Observations of **ground shaking** and **audible disturbances** collected by **Macroseismic questionnaire** of the Institute of Seismology, University of Helsinki
- More details: Krenz, Lukas, et al. "Numerical simulations of seismo-acoustic nuisance patterns from an induced M1. 8 earthquake in the Helsinki, southern Finland, metropolitan area." *arXiv preprint arXiv:2211.03647* (2022).

Induced Earthquakes & Reports



PGV and SPL maps



PGV: Horizontal Peak Ground Velocity

SPL: Sound pressure level, reconstructed from peak vertical velocity

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
- Differences will be important when connecting to tsunami observations
- Further application: Modeling **sound** generated by **induced earthquakes** (due to geothermal energy)
- Outlook: Fully-coupled models for Mediterranean tsunami (Hellenic arc), Húsavík-Flatey Fault Zone, North Iceland