Seismo-Acoustic Wavefield Simulations

Lukas Krenz[1], Sebastian Wolf[1], Alice-Agnes Gabriel[2], Gregor Hillers[3], Michael Bader[1]

[1] Technical University of Munich, [2]Scripps Institution of Oceanography, [3] University of Helsinki

Technical University of Munich

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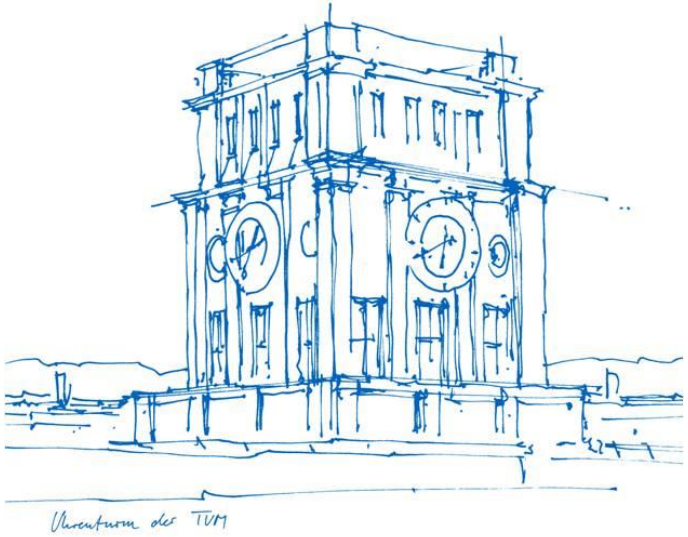


Otaniemi Project – Geothermal Energy & Seismic Hazards

Exploitation of geothermal energy is **controversially discussed** in the public:

“Many residents feel unsettled and are afraid of noise and cracks in buildings.” (TA, 2009-06-04)

"The resident describes the project as dangerous, incalculable, and full of contradictions.” (TA, 2009-06-09)"

Quotes via: Stauffacher, Michael, et al. "Framing deep geothermal energy in mass media: the case of Switzerland." Technological Forecasting and Social Change 98 (2015): 60-70.

Otaniemi project

- Enhanced geothermal system (EGS) In Greater Helsinki area
- Stimulated in June and July 2018
- Thousands of induced earthquakes
- No event exceeded threshold magnitude

Traffic Light System

Red: Stop; $M_L \geq 2.1$

Amber: Be Careful; PGV ≥ 1 mm/s detected and $M_L \geq 1.0$; $M_L \geq 1.2$

Green: Everything's fine

SCIENCE ADVANCES | RESEARCH ARTICLE

EARTH SCIENCES

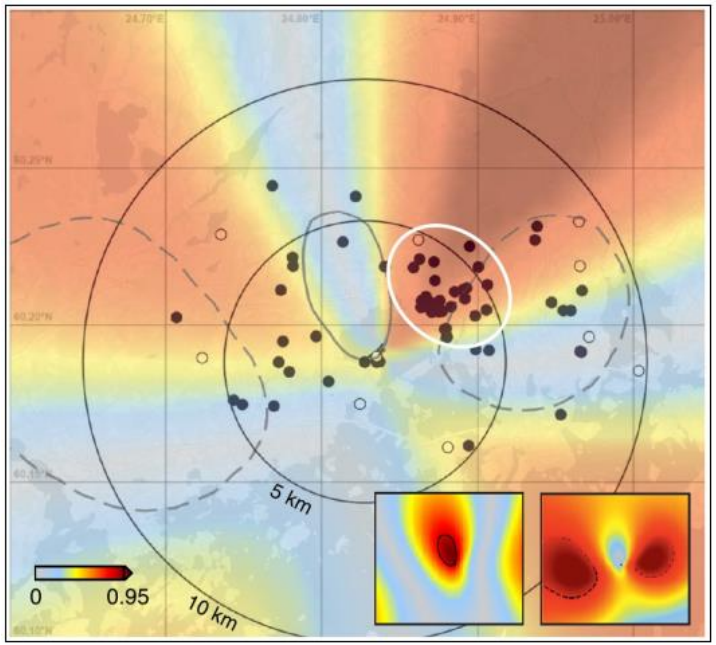
Controlling fluid-induced seismicity during a 6.1-km-deep geothermal stimulation in Finland

Grzegorz Kwiatek[1,2*], Tero Saarno[3], Thomas Ader[4], Felix Bluemle[1], Marco Bohnhoff[1,2], Michael Chendorain[4], Georg Dresen[1,5], Pekka Heikkinen[3,6], Ilmo Kukkonen[6], Peter Leary[7], Maria Leonhardt[1], Peter Malin[1,7], Patricia Martínez-Garzón[1], Kevin Passmore[7], Paul Passmore[7], Sergio Valenzuela[7], Christopher Wollin[1]

Design and implementation of a traffic light system for deep geothermal well stimulation in Finland

Thomas Ader · Michael Chendorain · Matthew Free · Tero Saarno · Pekka Heikkinen · Peter Eric Malin · Peter Leary · Grzegorz Kwiatek · Georg Dresen · Felix Bluemle · Tommi Vuorinen

Just Because It's Safe Doesn't Mean It's Not Annoying



Observations of **ground shaking** and **audible disturbances** collected by Macroseismic questionnaire of the Institute of Seismology, University of Helsinki

"*Big blast followed by a long 10-second echo*", Helsinki 2018-07-08 20:37

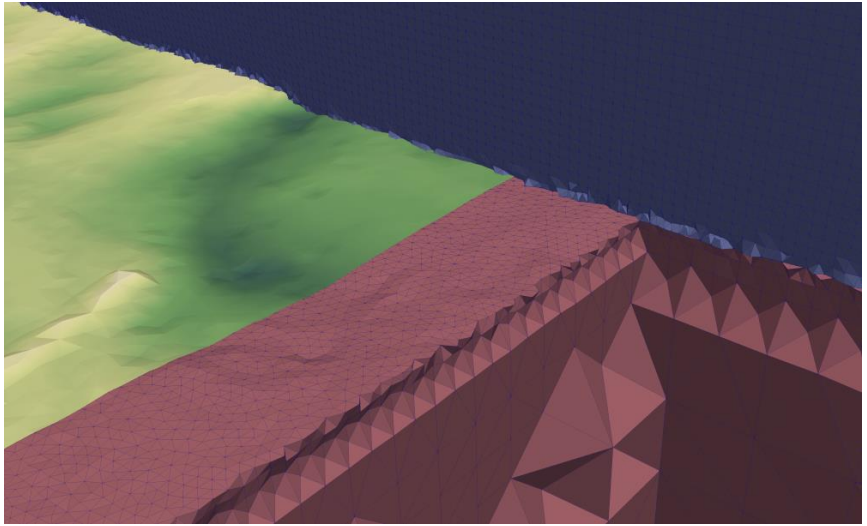
From: (Hillers et al., 2020).

SH wave radiation pattern

Filled & open circles: felt and heard disturbances were reported

Our Model[1]

- Model as point source using inversion from (G. Hillers et al., 2020)
- Fully **3D setup**, real topography, highly accurate ADER Discontinuous Galerkin method using SeisSol
- **Fully-coupled** elastic (Earth) - acoustic (air) simulation.
- Compute loudness by pressure perturbations of acoustic layer
- Need to resolve ~**20Hz**, preferable more



Snapshot of SeisSol mesh

[1]Krenz, Lukas, et al. The variability of seismo-acoustic nuisance patterns: a case study from the Helsinki geothermal stimulation. No. EGU22-10183. Copernicus Meetings, 2022.

Velocity Models

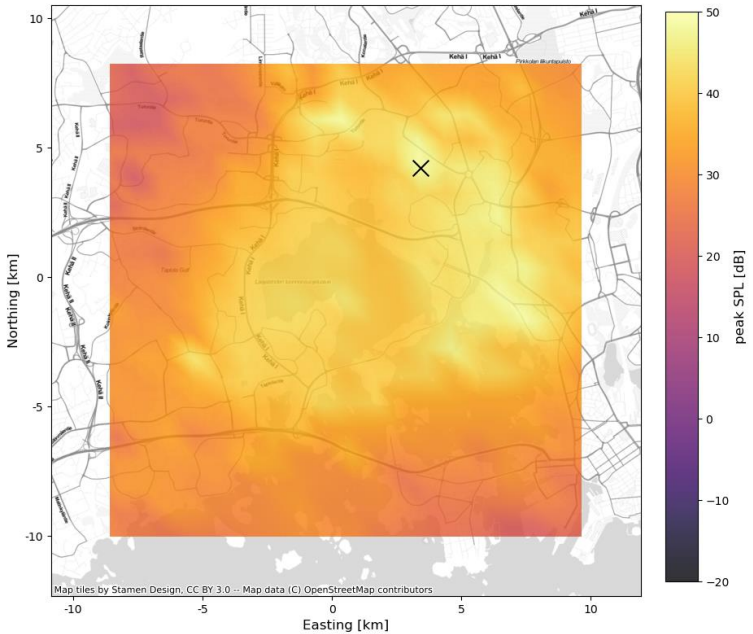
Slice through a 3D Velocity model. From Sisprobe (currently unpublished)

Idea: Generate "discomfort maps"

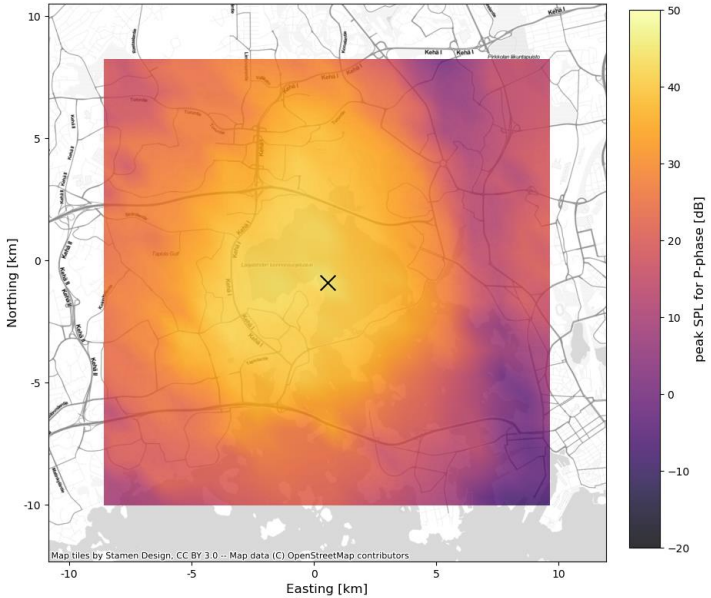
Visualize **spatial distribution** of **sound** as map

x/y Distance from epicenter

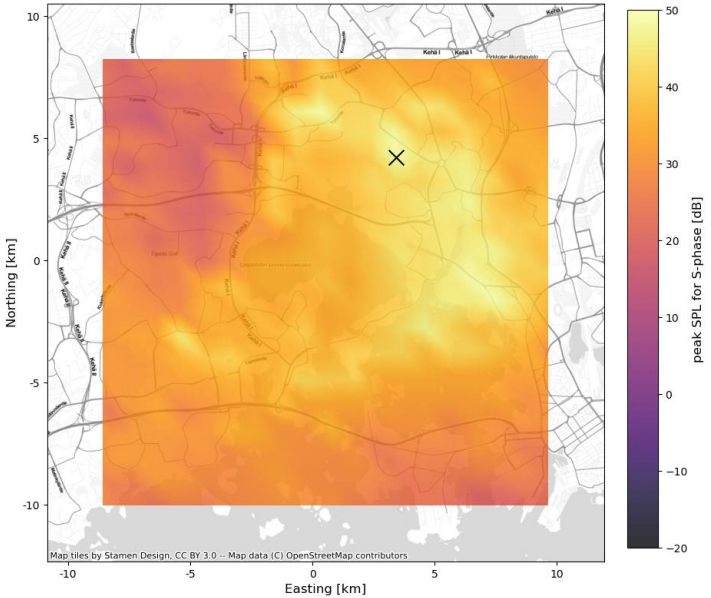
Color: Sound pressure level in decibel (logarithmic unit!)



Which phase is responsible for noise?



P(rimary) **wave**: Fast (6km/s)



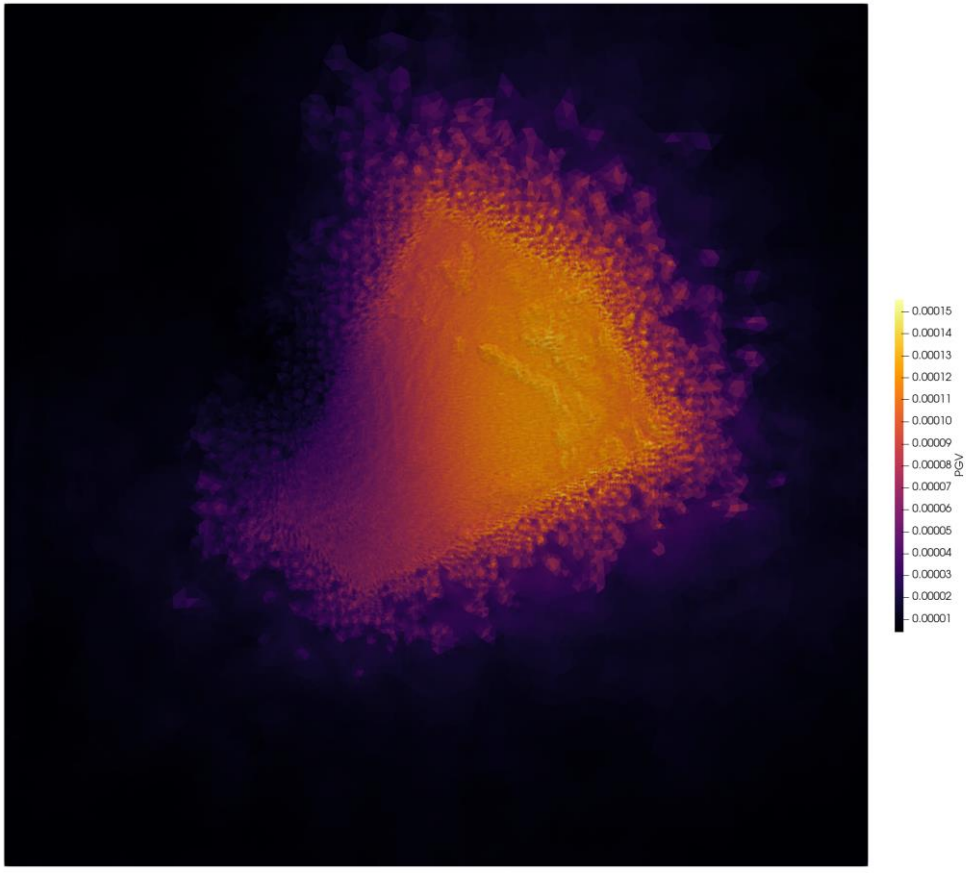
S(econdary) **wave**: Slower (~3.5km/s), often stronger

Peak Ground Velocity

Peak Ground Velocity (PGV) quantifies shaking

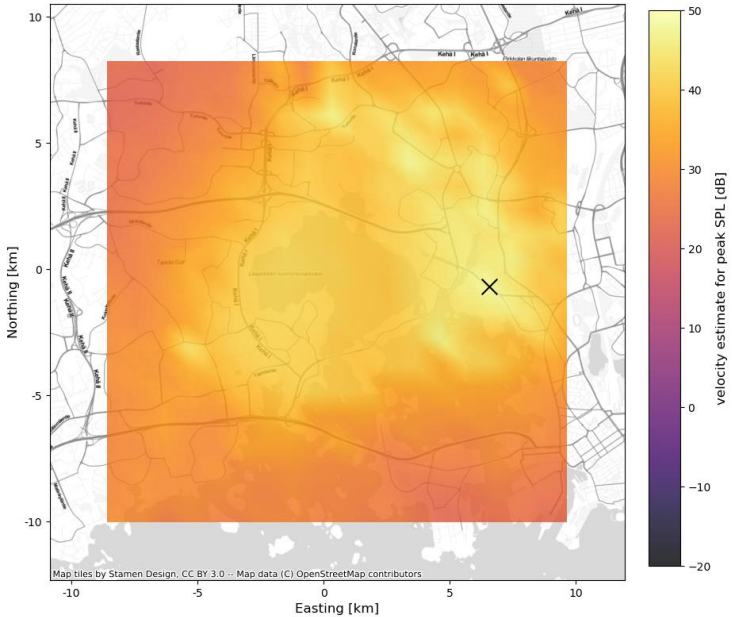
Visible here:

- Complex structure
- Overall polygon shape is our refinement structure

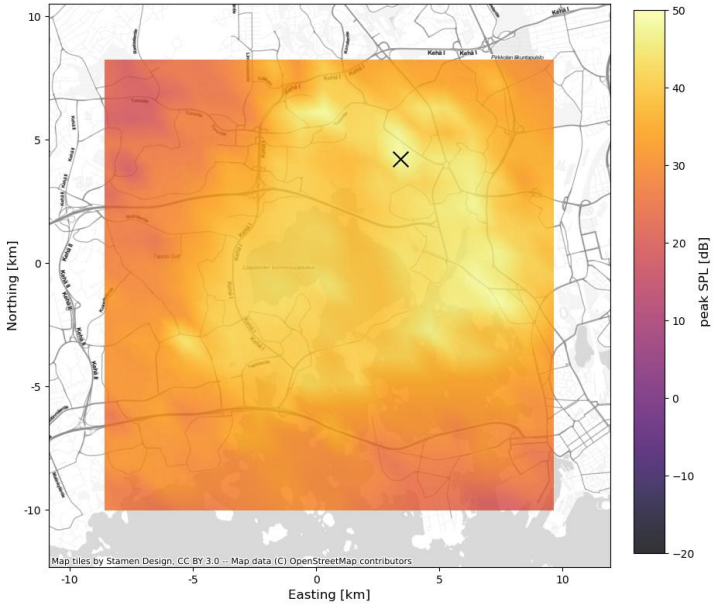


Approximating Pressure Perturbation

Approximation $\Delta P = \rho c v$ with ρ, c density/speed of sound in air; v vertical velocity on ground



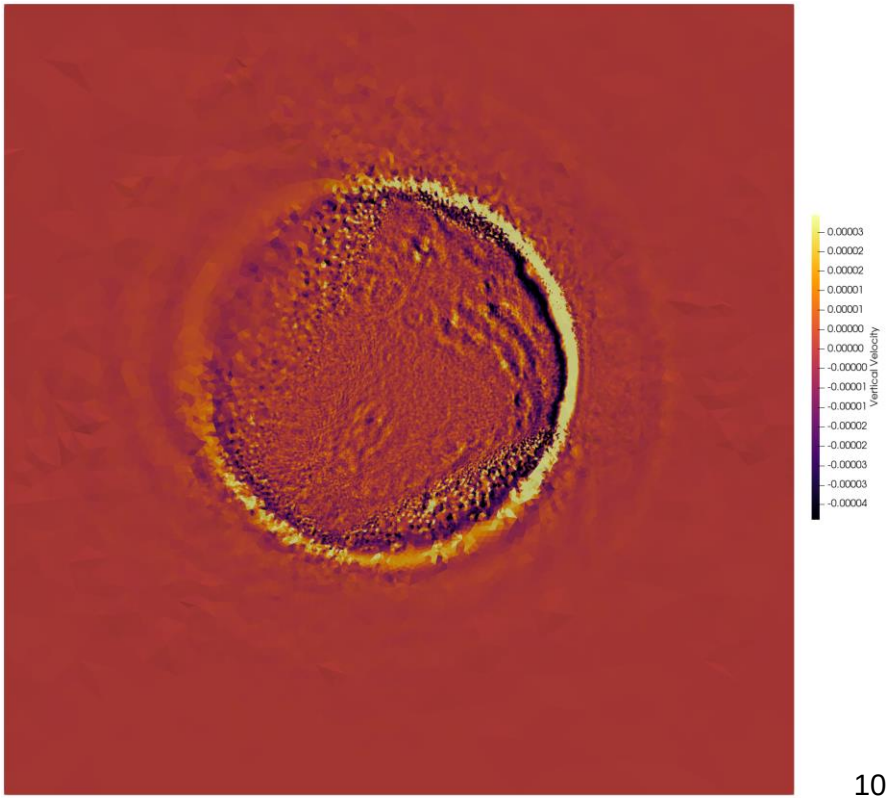
Comparison: Peak sound pressure level



Complex Wavefield at Surface

Wavefield at surface after 2s

Complex wavefield through interactions with topography



Conclusions & Further Work

- **Discomfort maps** show spatial distribution of noise generated by small, induced earthquakes. Important supplement to hazard maps
- **Simulated** spatial distribution of sound aligns with observations
- Further contribution: Evaluate **validity** of **common assumptions**:
  - Which phase is responsible for sound: both, but **mostly s-phase**
  - Can we approximate peak pressure from peak ground velocity: Yes, but not exactly

Further work:

- Case study with different material models and source models – *what if analysis*
- Paper will be submitted soon