Earthquake-induced seismic tremor explained by Krauklis wave resonance in fractured reservoir rocks: A case study of Salse di Nirano mud volcanic field (Italy)

Marcel Frehner and Matteo Lupi

Geological Institute
ETH Zurich
Switzerland
marcel.frehner@erdw.ethz.ch

Abstract

For seismic studies of fractured fluid-filled reservoir rocks, the so-called Krauklis wave is of particular interest. It is a special guided wave mode that is bound to and propagates along fluid-filled fractures. It can repeatedly propagate back and forth along a fracture and eventually fall into resonance. This resonant behavior has been speculated to be the source of narrow-band seismic tremor and long-period events in volcanic areas.

In the first part, we (Frehner, 2014) study Krauklis wave initiation by incident plane P- or S-waves using numerical simulations. In particular S-waves initiate Krauklis waves with significant amplitudes that strongly depend on the orientation of the facture. This has implications for earthquake signals propagating through fractured reservoirs, because Krauklis wave-related signals are expected to be present in seismic recordings.

In the second part, we assume that seismic tremor in the Salse di Nirano mud volcano after a M4.4 earthquake is due to Krauklis wave resonance triggered by the passing body waves. Using analytical Krauklis wave dispersion expressions, we relate the dominant earthquake and tremor frequencies to the fracture length. We propose that body waves initiate Krauklis wave resonance with a frequency peak distinctively different from the dominant earthquake frequency. The fractured reservoir traps certain frequencies and acts as a frequency-filter to body waves.

Numerical modeling stragegy

We use a self-developed finite-element code (Frehner and Schmalholz, 2010; Frehner, 2014) to simulate the propagation of seismic waves and the initiation of Krauklis waves by an incident body wave. The code is characterized by the following features:

- Visco-elastic governing equations, accounting for viscous damping in the fracture.
- Fracture is fully resolved by the numerical mesh.
- Unstructured numerical mesh using 7-node isoparametric triangular elements, allowing for element sizes varying by 4 orders of magnitude (i.e., very fine within and close to fracture, coarse far away from fracture).
- Implicit time integration, allowing for time increments independent of viscosity.

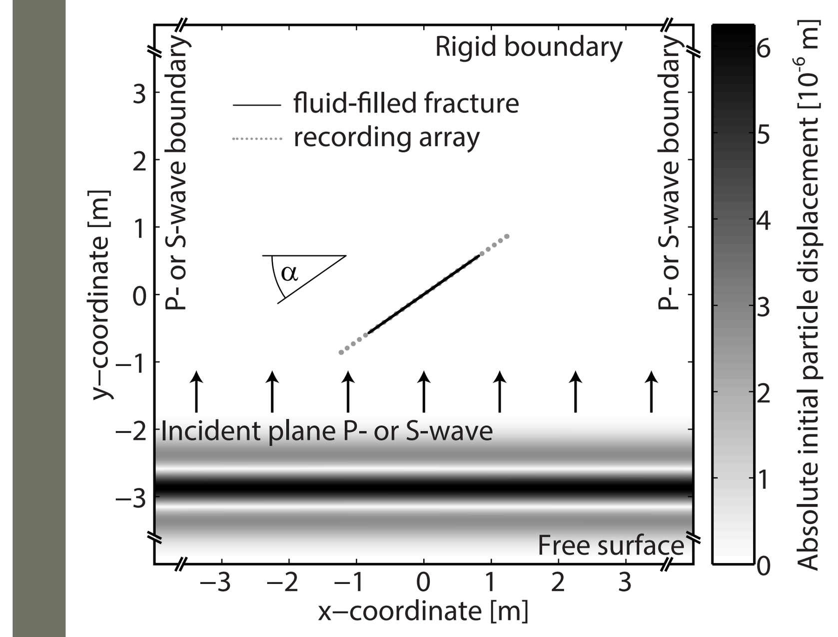

Fig. 1: Model setup for studying Krauklis wave initiation by an incident plane body wave. The boundaries are distant enough from the fracture to avoid any effects in the analyzed seismograms. The incident plane body wave is the second derivative of a Gaussian (Ricker wavelet). The fracture is numerically fully resolved and inclined by an angle α compared to the propagation direction of the body wave. The virtual seismic receiver line runs parallel and through the fracture.

Numerical results

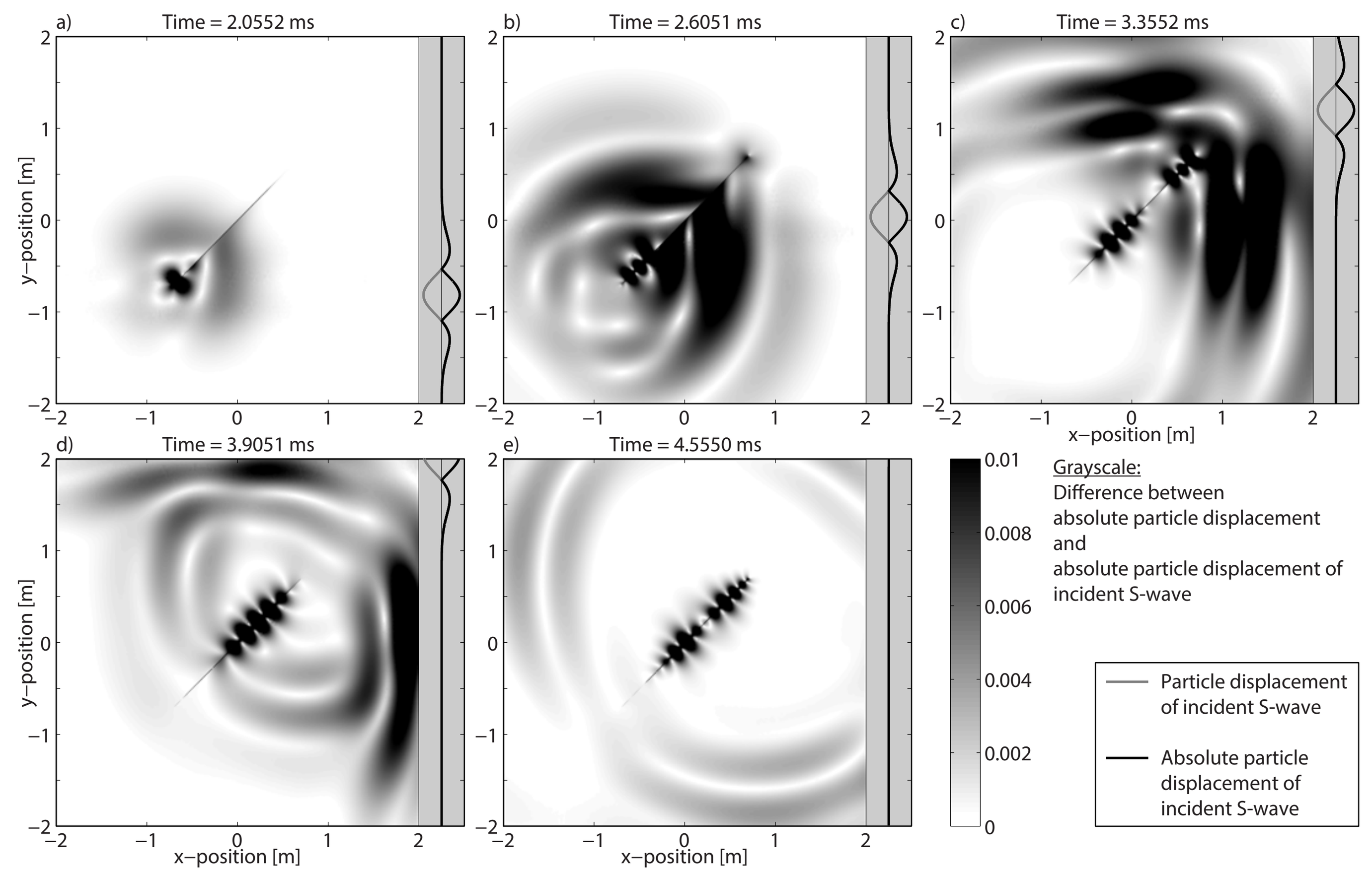

Fig. 2: Simulation example of a plane S-wave passing a water-filled fracture with inclination angle, α=45°. Gray shades show only secondary waves. Gray sidebars show the profile of the incident S-wave. Lobes propagating slowly along the fracture are the Krauklis waves.

Numerical simulations show that:

- Two Krauklis waves are initiated, one at each fracture tip (Fig. 2–3).
- Krauklis waves are the dominant secondary wave mode (Fig. 2–3).
- Krauklis wave initiation is more sensitive to S-waves (Fig. 4).
- Initiation strongly depends on fracture orientation (Fig. 4).

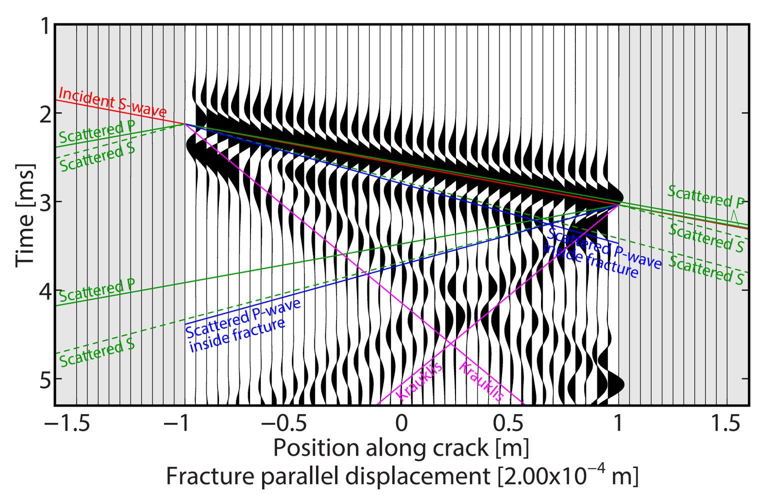

Fig. 3 (top): Seismic time section along the central receiver line (Fig. 1) for the simulation shown in Fig. 2. Gray and white areas correspond to receivers outside and inside the fracture, respectively. Straight lines represent theoretical phase velocities.

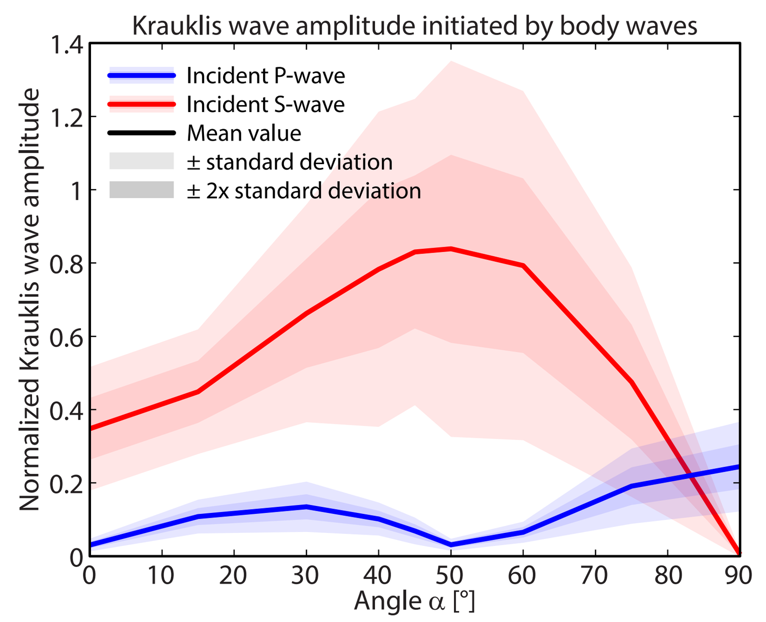

Fig. 4: Initiated Krauklis wave amplitude in fracture-parallel direction as a function of inclination angle α, normalized by the incident P- or S-wave amplitude.

Theoretical background for fracture-size estimation

We learned that body waves may initiate Krauklis waves. The Krauklis wave phase velocity for an inviscid fluid filling the fracture is given by (Ferrazzini and Aki, 1987):

$$V_{KW}=\left[\frac{\omega h\mu}{\rho_f}\left(1-\frac{V_S^2}{V_P^2}\right)\right]^{1/3}$$

where
- ω: angular frequency
- h: fracture thickness
- ρ_f: fluid density inside the fracture
- μ: elastic shear modulus, V_S: S-wave phase velocity, V_P: P-wave phase velocity — in the surrounding rock

Even though we use the more complete analytical solution of Korneev (2008), the equation above illustrates the relationship between the Krauklis wave phase velocity V_{KV}, the dominant input frequency ω, and the fracture thickness h.

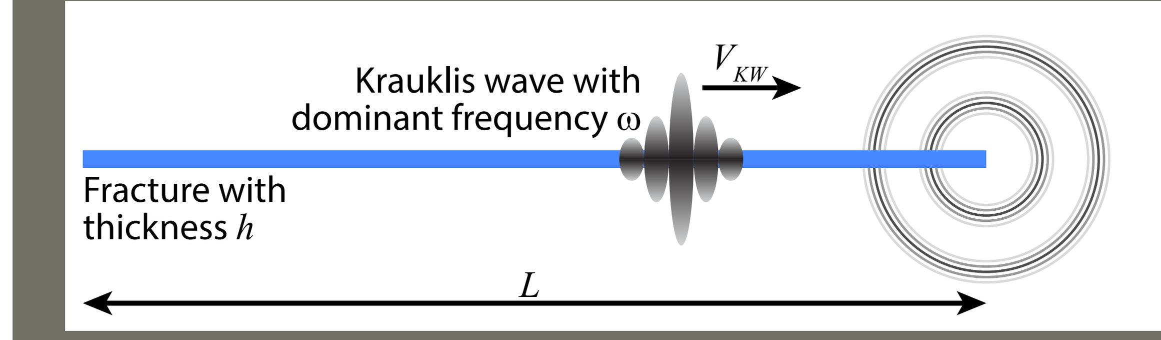

Fig. 5: Sketch of a Krauklis wave propagating back and forth along a fracture and diffracting at the fracture tip.

A Krauklis wave propagating back and forth along a fracture (length L) with phase velocity V_{KV} arrives at the fracture tip with a period of $2L/V_{KV}$ (Fig. 5); hence the tremor frequency generated by this oscillatory behavior is:

$$f_{tr}=\frac{V_{KW}}{4\pi L}$$

If we assume that a seismic tremor signal is produced by Krauklis waves resonating in a fractured reservoir, we can relate the input (trigger) frequency ω, the tremor frequency f_{tr}, and geometrical parameters of the fracture (L, h).

Case study: Salse di Nirano mud volcano, Italy

Continuously recorded broad-band seismic data eventually exhibits the following characteristics:

- Local M4.4 earthquake 30 June 2013 with a dominant frequency of **2 Hz (ω=12.57)**.
- Enhanced seismic tremor immediately after the earthquake with a dominant freuquency of **f_{tr}=18 Hz**.

The tremor is assumed to be due to initiated oscillating Krauklis waves.

Fig. 6: Satellite image showing the Salse di Nirano mud volcano in Italy.

Fracture-size estimation for the Salse di Nirano mud volcano

Using the theoretical relationships for the Krauklis wave phase velocity, we are able to construct a diagram of fracture length as a function of fracture thickness and dominant earthquake frequency (Fig. 7) for any given elastic material parameters of the fractured reservoir.

A whole range of fracture lengths and thickness combinations results in the same tremor frequency (Fig. 7–8). However, the fracture length saturates at a value of L_{max}=33 m.

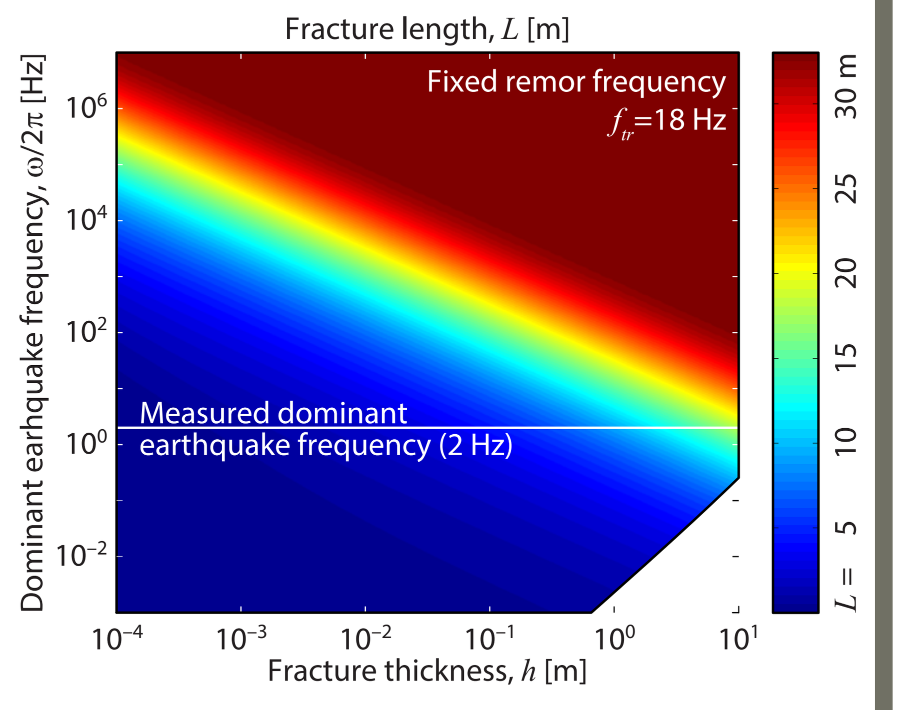

Fig. 7: Fracture length as a function of fracture thickness and dominant frequency of the triggering earthquake.

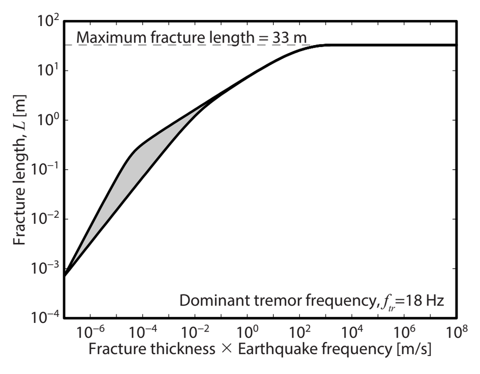

Fig. 8: All data of Fig. 7 plotted against the horizontal axis [fracture thickness multiplied with dominant earthquake frequency]. This horizontal axis represents diagonal sections through Fig. 7 and leads to an almost perfect data collapse.

Conclusions

- Body waves are capable of initiating Krauklis waves! This initiation depends strongly on fracture orientation and is more sensitive to incident S-waves than to P-waves.
- Hence, Krauklis wave-related seismic signals are to be expected in the coda of seismic events such as earthquakes or active seismic sources.
- Assuming that seismic tremor signals are caused by Krauklis waves falling into resonance allows relating geometrical fracture parameters to the dominant tremor frequency and the dominant trigger frequency.
- In the Salse di Nirano mud volcano, we showed that this relationship results in a dominant fracture length shorter than 33 m responsible for the seismic tremor.

Acknowledgements

This work was supported by the Swiss National Science Foundation (project UPseis, 200021_143319) and by the ETH Zurich Postdoctoral Fellowship Program.

References

Ferrazzini V. and Aki K., 1987: Slow waves trapped in a fluid-filled infinite crack: Implication for volcanic tremor, Journal of Geophysical Research 92, 9215–9223.
Frehner M., 2014: Krauklis wave initiation in fluid-filled fractures by seismic body waves, Geophysics 79, T27–T35.
Frehner M. and Schmalholz S.M., 2010: Finite-element simulations of Stoneley guided-wave reflection and scattering at the tips of fluid-filled fractures: Geophysics 75, T23–T36.
Korneev V., 2008: Slow waves in fractures filled with viscous fluid, Geophysics 73, N1–N7.