Krauklis wave initiation in fluid-filled fractures by a passing body wave: Theory, finite-element modeling and application to earthquake-induced mudvolcanic seismic tremor

Marcel Frehner and Matteo Lupi

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

Krauklis waves are a special seismic wave mode that is bound to and propagates along fluid-filled fractures (Ferrazzini and Aki, 1987; Korneev, 2008). They can repeatedly propagate back and forth along a fracture and eventually fall into resonance emitting a seismic signal with a dominant characteristic frequency. They are of great interest because this resonant behavior can lead to strongly frequency-dependent propagation effects for seismic body waves and may explain seismic tremor generation in volcanic areas (Chouet, 1988; Chouet, 1996) or affect micro-seismic signals in fractured fluid reservoirs. It has been demonstrated that Krauklis waves can be initiated by a seismic source inside the fracture (Frehner and Schmalholz, 2010), for example by hydrofracturing (Ferrazzini et al., 1990) or when a fracture intersects a borehole (Ionov, 2007). However, it remains unstudied whether Krauklis waves can be initiated by body waves, and therefore be really relevant for active seismic surveys in fractured reservoir situations or for seismic earthquake signals traveling through fractured rocks.

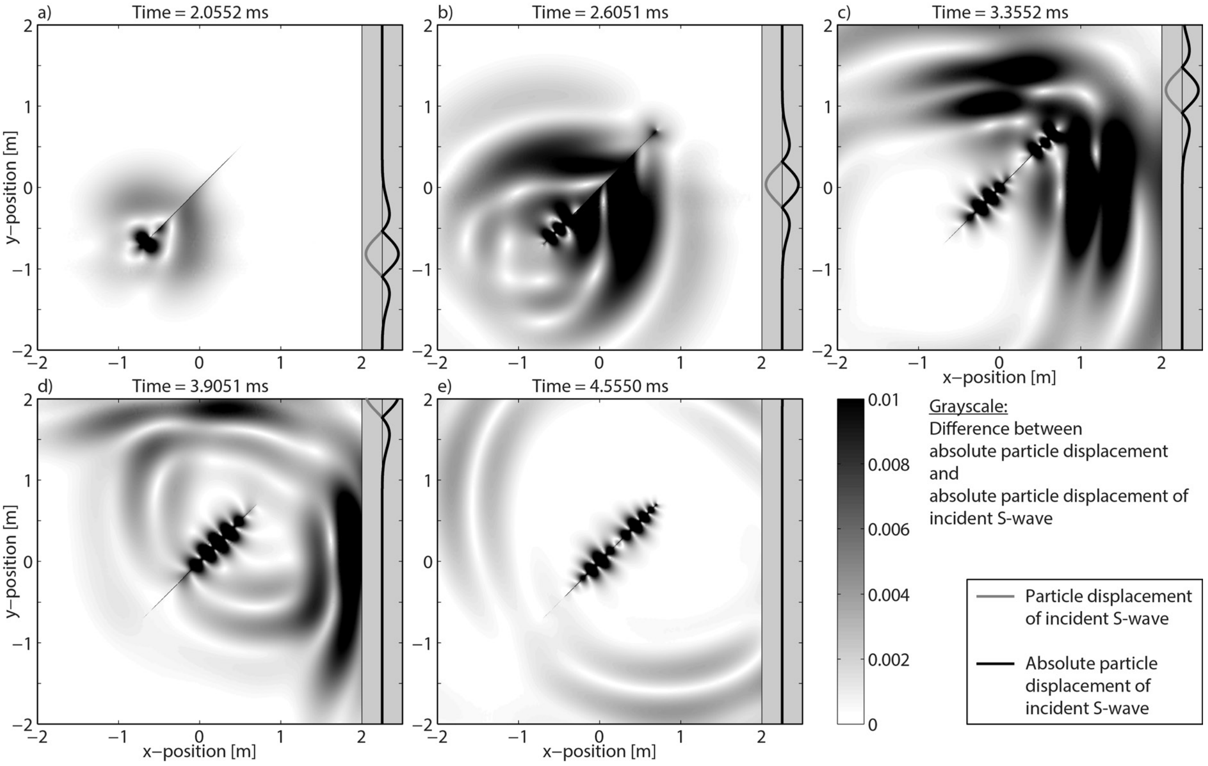

Figure 1: Simulation snapshots of a plane S-wave passing a water-filled fracture with an inclination angle of 45°. The incident S-wave consisting of a single Ricker wavelet is propagating from the bottom of the model towards the top, and its profile is shown in the gray sidebars of each subfigure. Gray shades display the differential absolute particle displacement of the wavefield (i.e., the difference between the total wavefield and the incident S-wave).

In the first part of the study, Krauklis wave initiation by an incident plane P- or S-wave is studied using numerical finite-element simulations (Frehner, 2013; Frehner, 2014). It is found that both seismic body waves are reflected and scattered at the fracture, but also, that two Krauklis waves are initiated with significant amplitude, one at each fracture tip (i.e., at the diffraction-points of the fracture). Generally, incident S-waves initiate larger-amplitude Krauklis waves compared to an incident P-wave. For both incident wave modes, the initiation of Krauklis waves strongly depends on the fracture orientation. In the case of an incident P-wave, large-amplitude Krauklis waves are initiated at moderate (12°–40°) and high (>65°) inclination angles of the fracture with a distinct gap at approximately 50°. In the case of an incident S-wave, the dependency of Krauklis wave initiation on fracture orientation is almost inversed and the largest-amplitude Krauklis waves are initiated at an S-wave incidence angle of approximately 50°. Knowing that both P- and S-waves are able to initiate large-amplitude Krauklis waves has some severe implications as they should lead to strongly frequency-dependent and anisotropic propagation behavior for body waves in situations where seismic body waves propagate through fluid-filled fractured rocks.

Once Krauklis waves are initiated, either by body waves or by a seismic source inside the fracture, they propagate along the fracture. Yet, their signal cannot be detected at a relatively short distance from the fracture because their amplitude spatially decays exponentially away from the fracture (Ferrazzini and Aki, 1987). However, Frehner and Schmalholz (2010) demonstrated that Krauklis waves both reflect and diffract at fracture tips and at intersection points between two fractures. The diffraction of Krauklis waves emits body waves into the surrounding rock, which then propagate away from the fracture. Therefore, it can be assumed that Krauklis wave-related signals can also be recorded further away from the fracture, for example at seismic stations at the Earth's surface.

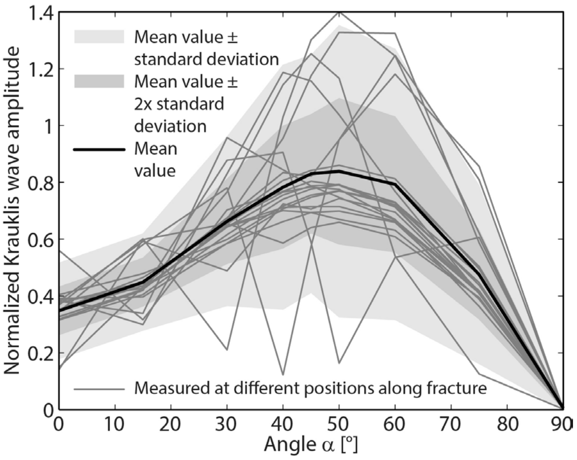

Figure 2: Krauklis wave amplitude in the fracture-parallel direction, normalized by the incident S-wave amplitude, as a function of the inclination angle of the fracture.

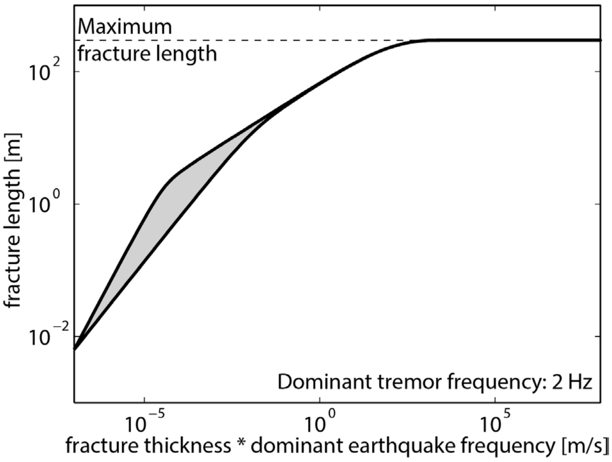

Figure 3: Fracture length as a function of fracture thickness and the dominant frequency of the triggering earthquake. The measured dominant tremor frequency is 2 Hz.

The second part of the study is a direct application of the conclusion of the first part, that Krauklis waves can be initiated by passing body waves. Seismic tremor signals around the Salse di Nirano mudvolcano in northern Italy are analyzed assuming that Krauklis wave-related signals are present in the recorded seismograms. Immediately after an earthquake, the seismic tremor increased and its frequency content was much more narrow-banded than before the earthquake with a frequency-peak at around 2 Hz. Apparently, the seismic body waves from the earthquake excited a resonant behavior of the mudvolcano system, and it is assumed that this resonant behavior is due to Krauklis waves being initiated by the passing body waves. Based on these assumptions, the analytical solution for the

Krauklis wave phase velocity (Korneev, 2008) is used to estimate the maximum fracture length in the mudvolcano system. This analytical solution relates the frequency-dependent phase velocity with the fracture thickness and the petrophysical parameters of the mudvolcano system. The latter can be taken from the literature. As a result, the geometrical parameters of the fractures (thickness and length) can be related to the observed dominant tremor frequency. To visualize this relationship, a kind of phase diagram is created, which makes it easy to read the geometrical parameters of the fracture. In the studied mudvolcano system, the maximum fracture length is found to be in the order of few 100 m.

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