Initiation of Krauklis waves by incident seismic body waves:
Numerical modeling, laboratory perspectives, and application for fracture-size estimation

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Summary

Krauklis waves (i.e., fracture-guided waves) are of key interest because they can lead to seismic resonance effects in fluid-filled fractured rocks and may explain the origin of the dominant frequency of seismic tremor. Here, we study the external initiation of Krauklis waves by incident P- and S-waves. We split our study into three parts:

1. A numerical study demonstrating that body waves are capable of initiating Krauklis waves with significant amplitude. We show how this initiation depends on fracture orientation and incident wave mode.
2. A snapshot of work in progress in the laboratory. First results show that the presence of a fracture has a strong frequency-effect on body wave propagation.
3. Application of theoretical Krauklis wave dispersion relations to estimate the fracture size in a natural fluid reservoir (below a mud volcano) using tremor data.

Introduction

Krauklis waves are a guided wave mode bound to and propagating along fluid-filled fractures (Krauklis, 1962; Ferrazzini and Aki, 1987; Korneev, 2008). As they propagate back and forth along a fracture, they can fall into resonance and act as a seismic source with a characteristic frequency. This resonant behavior can lead to strongly frequency-dependent propagation effects (Korneev et al., 2009) and may explain the origin of volcanic tremor (Chout, 1988; Chout, 1996) or may affect micro-seismic signals in fractured fluid reservoirs.

A seismic source inside the fracture (e.g., hydrofracturing; Ferrazzini et al., 1990) can evidently initiate Krauklis waves (Frehner and Schmalholz, 2010). However, for Krauklis waves to be relevant for active seismic surveys in fractured reservoirs or for earthquake signals propagating through fractured rocks, they have to be initiated by body waves, which is the main focus of the investigation here.

Numerical Modeling

We study Krauklis wave initiation using a self-developed finite-element (FE) code that simulates two-dimensional (2D) visco-elastic wave propagation (Frehner et al., 2008; Frehner and Schmalholz, 2010). The water-filled fracture is numerically fully resolved. The water exhibits a visco-elastic rheology while the surrounding rock is fully elastic. The source is a plane P- or S-wave (Ricker wavelet) with a wavelength similar to the fracture length.

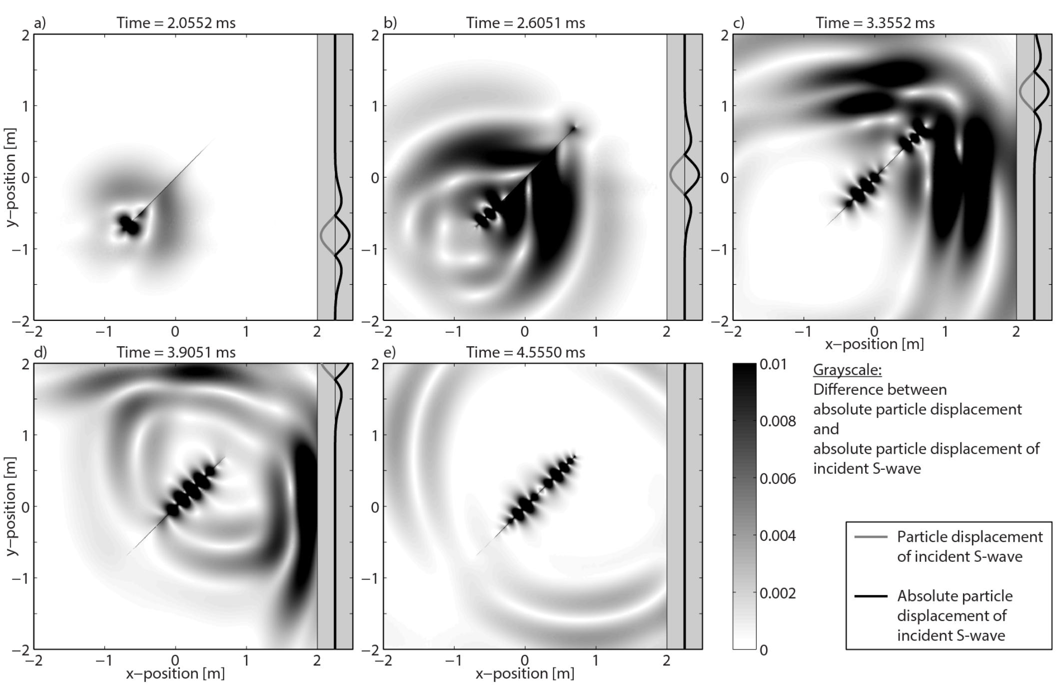


Figure 1: Simulation snapshots of a plane S-wave passing a water-filled fracture with an inclination angle of 45°. Gray shades represent the absolute value of the difference between the total wave field and the incident S-wave field; hence only secondary waves are visible. The incident S-wave is a Ricker wavelet propagating from the bottom to the top; its profile is shown in the gray sidebars of each subfigure. The slowly propagating lobes along the fracture are the initiated Krauklis waves.

Numerical Simulation Results

FE-simulation snapshots (Figure 1) and seismic time sections of a receiver line along and inside the fracture (Figure 2) demonstrate that an incident S-wave is capable of initiating Krauklis waves with significant amplitude. Two Krauklis waves are initiated, one at each fracture tip corresponding to the diffraction points of the fracture. The seismic time section (Figure 2) also demonstrates that the Krauklis waves are the only initiated secondary waves in the fracture; all other secondary waves are negligible. This observation also holds for all other simulations.

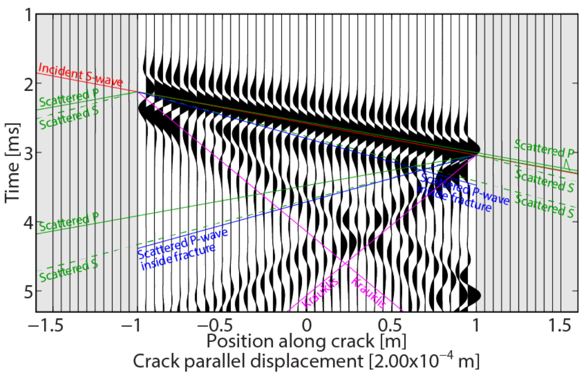


Figure 2: Seismic time section of the fracture-parallel difference between the total wave field and the incident S-wave field on the receiver line along and inside the fracture for an inclination angle of 45°. Gray and white shaded areas correspond to receivers outside and inside the fracture, respectively. Straight lines represent theoretical phase velocities of different wave modes.

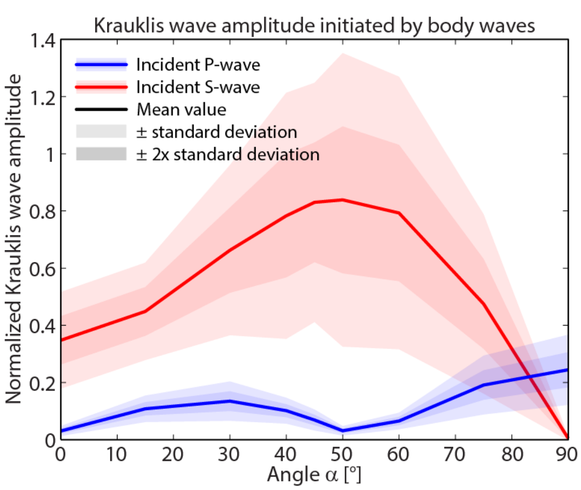
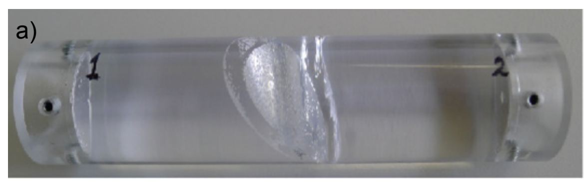


Figure 3: Initiated Krauklis wave amplitude in fracture-parallel direction, normalized by the incident P- or S- wave amplitude, as a function of the inclination angle α. Because the initiated amplitudes also depend on the position along the receiver line, results are plotted as the mean value ± standard deviation.

From the seismic time sections of a series of simulations (see also Frehner, 2013; Frehner, 2014), we calculated the amplitude of the initiated Krauklis wave (Figure 3) as a function of inclination angle and incident wave mode (P- or S-wave). S-waves initiate much larger amplitude Krauklis waves than P-waves, except if the incident wave propagates parallel to the fracture (α=90°). The largest-amplitude Krauklis waves are initiated by S-waves at an inclination angle of about 50°, which is also the angle where P-waves initiate the smallest-amplitude Krauklis waves.

Laboratory Measurements

To mimic the simplified numerical setup, we started our laboratory investigations with a Plexiglas sample containing one single fracture (Figure 4). To manufacture the fracture, we cut the sample in the middle at an angle of 45°, drilled a 0.1 mm deep elliptical hole on one side, and glued the two pieces back together with chloroform. We perform standard pulse transmission experiments (source at position 1; receiver at position 2 in Figure 4a) using the intact and the fractured sample and compare the two cases.



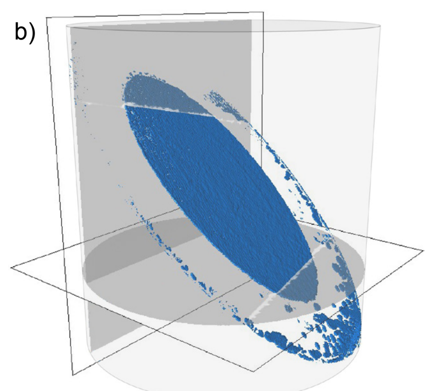


Figure 4:
a) Plexiglas sample (120 mm length, 25 mm diameter) with manufactured elliptical fracture (0.1 mm thickness).
b) Segmented micro-CT scan of the sample (transparent gray) containing the manufactured fracture (blue).

Preliminary Laboratory Results

So far, we only tested our laboratory assembly for P-waves. The seismic signal is recorded and transformed into the frequency-domain either by a Fast Fourier Transform (FFT) or by calculating the multitaper power spectral density (PSD). For both methods, the ratio between the frequency-signals with and without fracture (Figure 5) reveals a strong frequency-effect of the manufactured fracture. In the fractured case, the signal is strongly enhanced at around 1 MHz compared to the intact sample (amplitude ratios larger than 1 in Figure 5). Other frequencies are much less affected by the fracture. This suggests that the presence of the fracture indeed leads to a resonance effect and to an enhancement of a characteristic frequency (i.e., the resonance frequency).

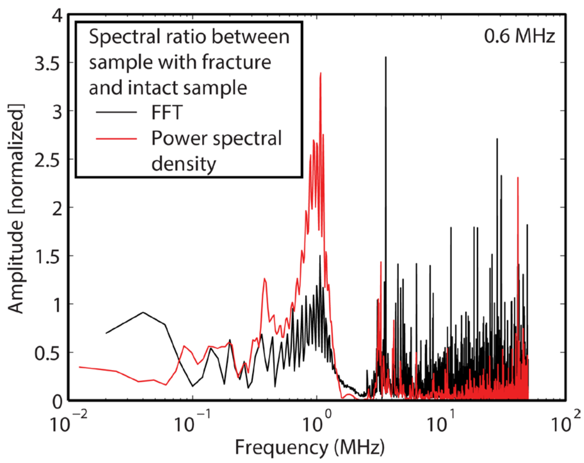


Figure 5: Spectral ratio between receiver signals of the fractured and the intact sample using a 0.6 MHz source signal. A broad peak of fracture-related attenuation can be identified at around 1 MHz.

Our laboratory study is just in its initial state. Our next step is to also measure incident S-waves at an inclination angle of 45°, because this is the configuration where we expect the largest influence of the fracture (Figure 3). After that, we will test for different inclination angles to try reproducing the Krauklis sensitivity curve predicted by the numerical models (Figure 3). Finally, we will also employ natural samples representative for fractured reservoirs.

Application: Fracture-size estimation in the Salse di Nirano mud volcano, Italy

From the above numerical and preliminary laboratory results we learned that body waves are capable of initiating Krauklis waves in fractures and that the presence of fractures strongly influences the propagation behavior of body waves. Knowing this, we can assume that seismic waves from earthquakes initiate Krauklis waves in fluid-filled fractured rocks. Once initiated, Krauklis waves can propagate back and forth along a fracture (Frehner and Schmalholz, 2010) and eventually fall into resonance. This rock-internal resonance leads to a strongly frequency-dependent propagation behavior for the incident body waves (Frehner et al., 2009; Frehner et al., 2010; Steeb et al., 2010; Steeb et al., 2012) and to the enhancement of a characteristic frequency (i.e., the resonance frequency).

We expect that after a strong seismic event (e.g., active seismic source or earthquake) the initiated Krauklis waves in a fractured fluid reservoir continue oscillating for a short time after the seismic trigger. Hence, we expect enhanced seismic tremor in the immediate aftermath of a seismic event with a characteristic frequency related to the fracture size. To test this hypothesis, we use seismic recordings at the Salse di Nirano mud volcano (Figure 6) in northern Italy. We analyzed the seismic coda signal after a local earthquake on 30. June 2013. We prefer considering a local earthquake in contrast to a teleseismic one, because we can assume that large-amplitude body waves propagate at the depth of the fluid reservoir of the mud volcano.

Figure 6: Satellite image showing the geographical location of the Salse di Nirano mud volcano in northern Italy.

Fracture-size estimation

The local earthquake at the Salse di Nirano mud volcano exhibited a dominant frequency of 2 Hz. The subsequent seismic tremor signal exhibited a dominant frequency of 18 Hz. We assume that the seismic event initialized Krauklis waves, whose resonant behavior led to the dominant tremor frequency. We use the existing analytical expressions to determine the Krauklis wave phase velocity. For a non-viscous fluid filling the fractures, the Krauklis wave phase velocity is (Ferrazzini and Aki, 1987)

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

where ω is frequency, h is the fracture thickness, μ is the elastic shear modulus of the surrounding rock, ρ_f is the fluid density inside the fracture, and V_S and V_P are the S- and P-wave phase velocities in the surrounding rock. In fact, we use the more complete analytical solution of Korneev (2008). Nevertheless, Equation (1) illustrates the relationship between the Krauklis wave phase velocity, the dominant frequency, and the fracture thickness.

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If we assume that the dominant tremor frequency is a result of Krauklis waves propagating with velocity V_{KW} back and forth along fractures, we can derive a relationship between the dominant earthquake frequency (ω), the fracture thickness (h), and the fracture length (L) for a given tremor frequency and given elastic parameters (Figure 7a). For the studied seismic event, the fracture length is a function of the multiplied fracture thickness and earthquake frequency (Figure 7b). The Krauklis wave velocity increases with increasing fracture thickness (Equation 1); hence the fracture length required for resonance with the observed tremor frequency also increases (positive slope in Figure 7b). However, the analytical expressions for fracture length saturate at a maximum value of 33 m. We therefore estimate the majority of fractures in the Salse di Nirano mud volcanic system to be no longer than 33 m.

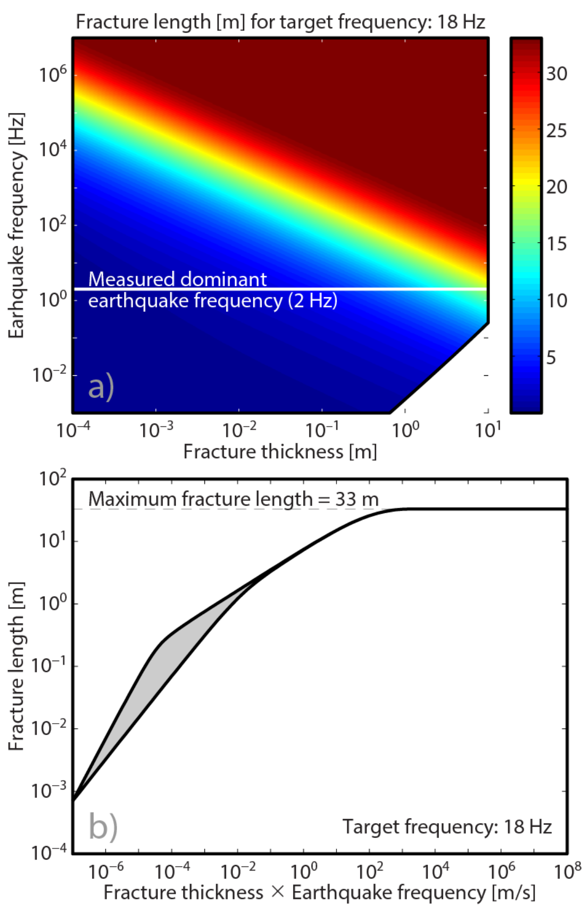

Figure 7: a) Fracture length as a function of fracture thickness and dominant frequency of the triggering earthquake for a dominant tremor frequency of 18 Hz. b) All data of a) plotted against the horizontal axis [fracture thickness multiplied with dominant earthquake frequency]. This horizontal axis represents diagonal sections through a) and leads to an almost perfect data collapse.

Discussion

Compared to our numerical and laboratory study, natural fracture systems are much more complex (e.g., intersecting fractures, uneven fracture surfaces, etc.). Therefore, more diffraction points are present and we expect the potential to initiate Krauklis waves to be much higher in nature. Because Krauklis wave initiation strongly depends on fracture orientation (Figure 3), we expect that seismic recordings carry this information, in particular S-waves.

Previous studies (Ferrazzini et al., 1990; Frehner and Schmalholz, 2010) showed that a seismic source inside a fracture initiates large-amplitude Krauklis waves. In the case of hydrofracking, the initiated Krauklis wave carries energy away from the hydrofrac-source along the fracture and emits body waves at other diffraction points of the fracture. This secondary seismic source shortly after the hydrofrac-event may reduce the localization accuracy of hydrofracking-related microseismic events.

Once Krauklis waves are initiated they can propagate back and forth along a fracture, resulting in a rock-internal oscillation effect. Earlier studies (Steeb et al., 2012) demonstrated that such effects result in a frequency-shift of the dispersion and attenuation curves. These frequency-shifted dispersion and attenuation relations can be described by effective poro-elastic rock properties, which however do not represent the true properties. Therefore, we warn from wrongly estimated poro-elastic rock properties in fracture-dominated rocks.

Conclusions

Our numerical and laboratory measurements demonstrate that the presence of fractures significantly alters the propagation of body waves. The numerical study in particular showed that body waves initiate Krauklis waves in fluid-filled fractures. We predict that also in natural situations, body waves (e.g., active seismic surveys or earthquake signals) initiate Krauklis waves and are therefore altered. The effect for body waves strongly depends on fracture orientation and frequency. Assuming that tremor signals in the coda of seismic events 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 fracture length shorter than 33 m.

Acknowledgements

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