Reflection and scattering of Stoneley guided waves (SGW) at the tips of fluid-filled fractures

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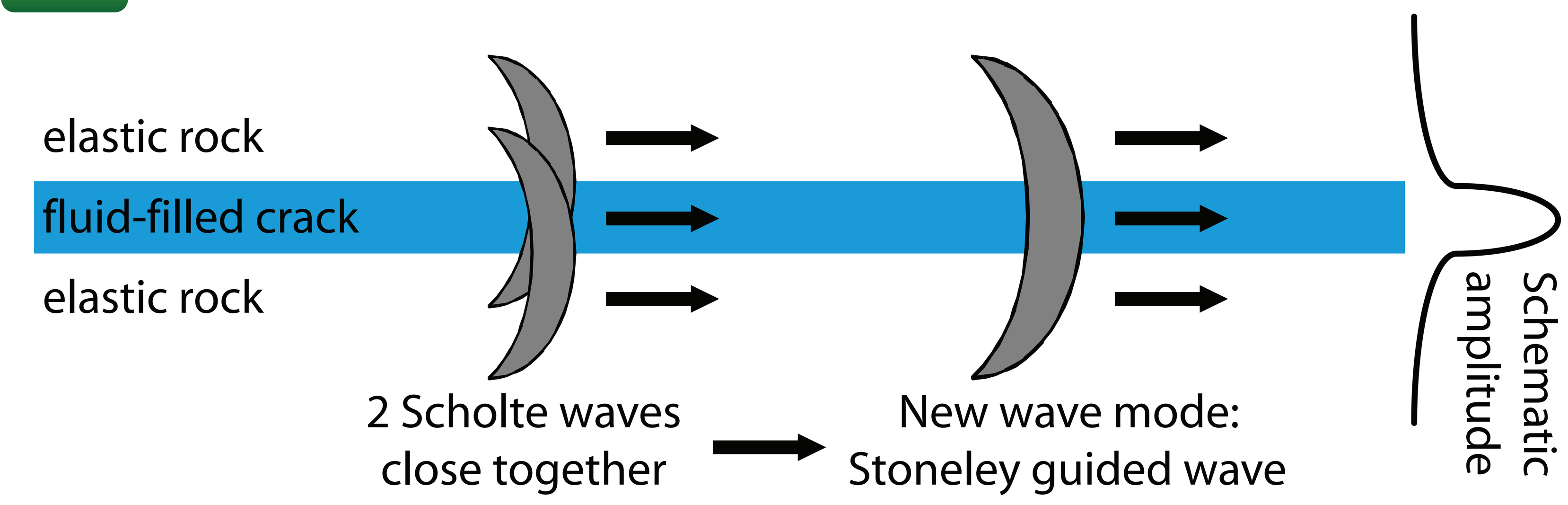
Summary

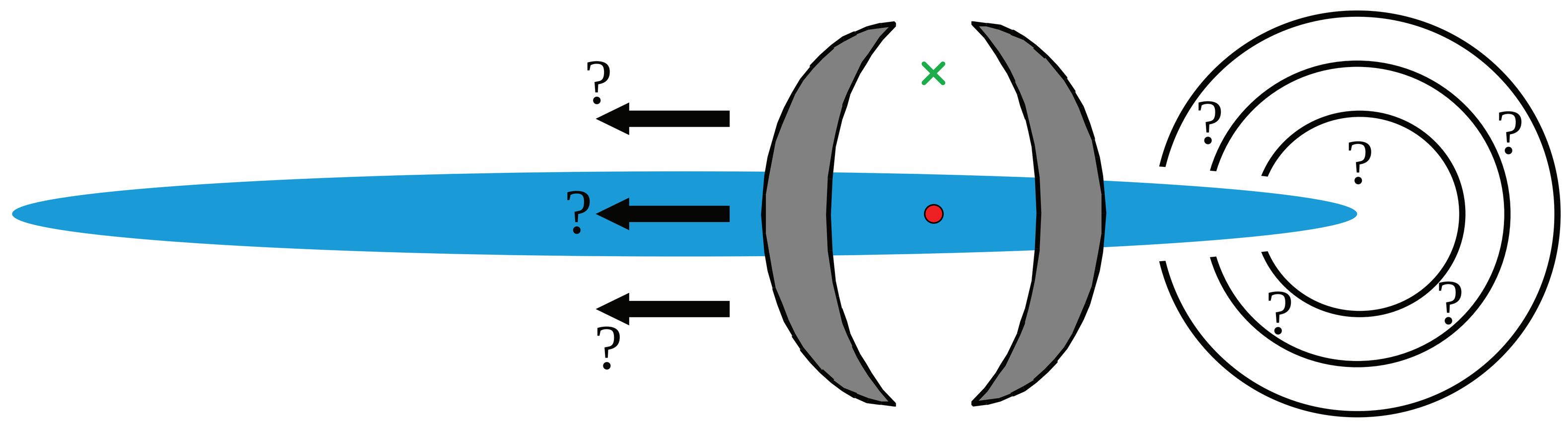
Reflection and scattering of Stoneley guided waves (SGWs) at the tip of a crack filled with a viscous fluid is studied numerically in two dimensions using the finite element method. The rock surrounding the crack is fully elastic and the fluid filling the crack is elastic in its bulk deformation behavior and viscous in its shear deformation behavior. The crack geometry, especially the crack tip, is resolved in detail by the unstructured finite element mesh. At the tip of the crack the SGW is reflected. The amplitude ratio between reflected and incident SGW is calculated from numerical simulations, which provide values between 43% and close to 100%, depending on the type of fluid filling the crack (water, oil or hydrocarbon gas), the crack geometry (elliptical or rectangular) and the presence of a small gas cap at the crack tip. The interference of incident and reflected SGWs leads to a node (zero amplitude) at the tip of the crack. At other positions along the crack this interference increases the amplitude. However, the exponential amplitude decay away from the crack makes the SGW difficult to detect at a relatively short distance away from the crack. The part of the SGW that is not reflected is scattered at the crack tip and emitted into the surrounding elastic rock as body waves. For fully saturated cracks the radiation pattern of these elastic body waves points in every direction from the crack tip. The emitted elastic body waves may allow detecting SGW-related resonant signals at distances away from the crack where the amplitude of the SGW itself is too small to be detected.

What are SGWs?

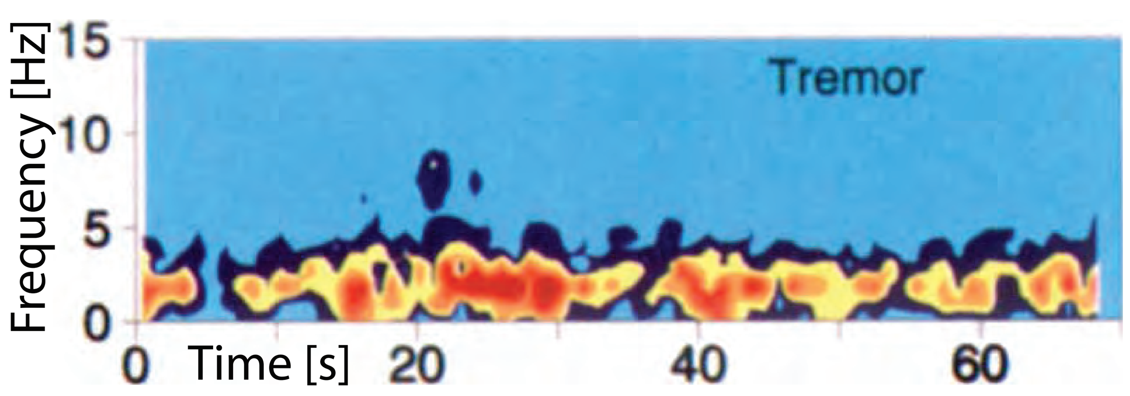


- Scholte wave: Interface wave between solid and fluid
- Interference between two Scholte waves propagating very close together leads to a new wave mode: The Stoneley guided wave
- Properties: Strongly dispersive (V_{SGW}=0 for f=0)
  Not attenuating for inviscid fluids
- Ferrazzini and Aki, JGR (1987); Korneev, Geophysics (2008)

Why are SGWs interesting?



- SGWs can exhibit a resonance frequency when propagating back and forth along a finite crack.
- Used for explaining low-frequency volcanic tremor (e.g. Chouet, Nature 1996)
- This study focusses on the reflection process.

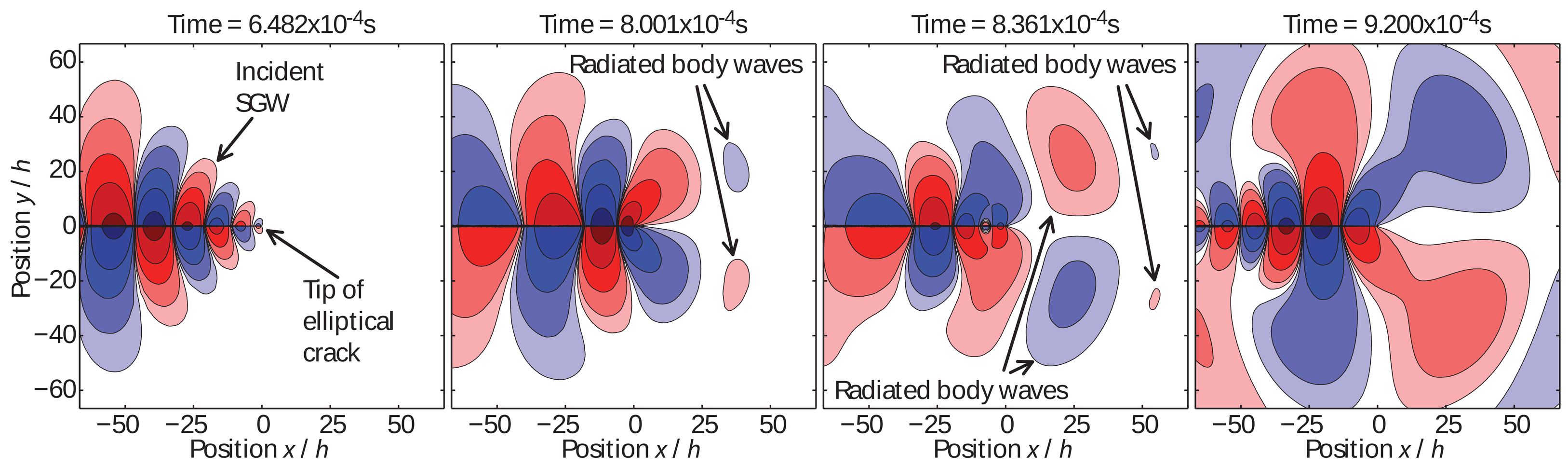


Chouet, Nature (1996)
Volcanic tremor, Mt. Redoubt, Alaska
Continuous narrow-band seismic signal

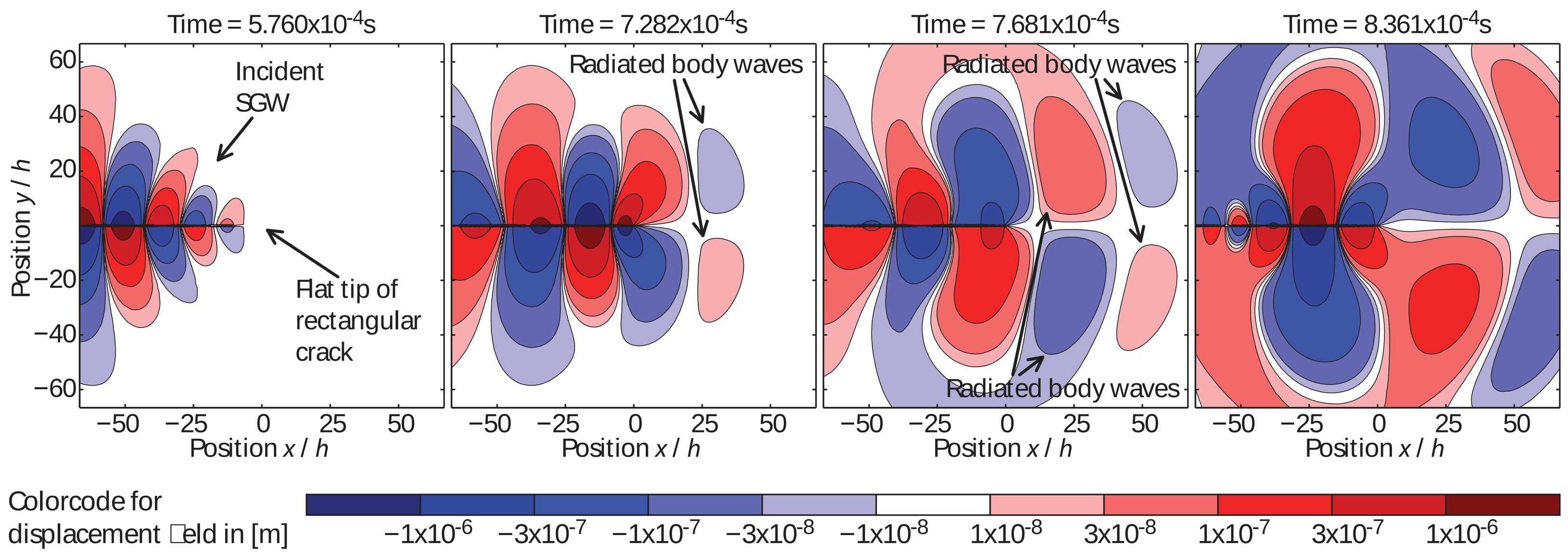
Radiation pattern

Finite element simulations of SGWs reflecting at the tip of water-filled cracks. Vertical displacement is displayed. Crack thickness : Wave length ≈ 1 : 100

Elliptical crack: Low- amplitude radiation

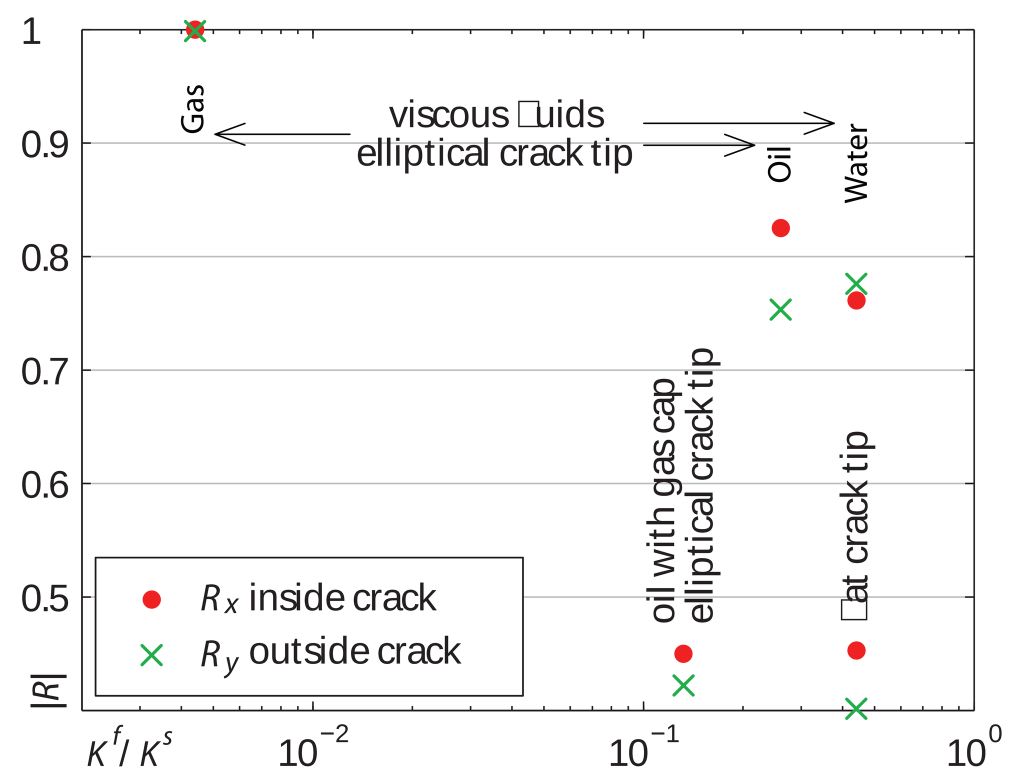


Rectangular crack: High- amplitude radiation



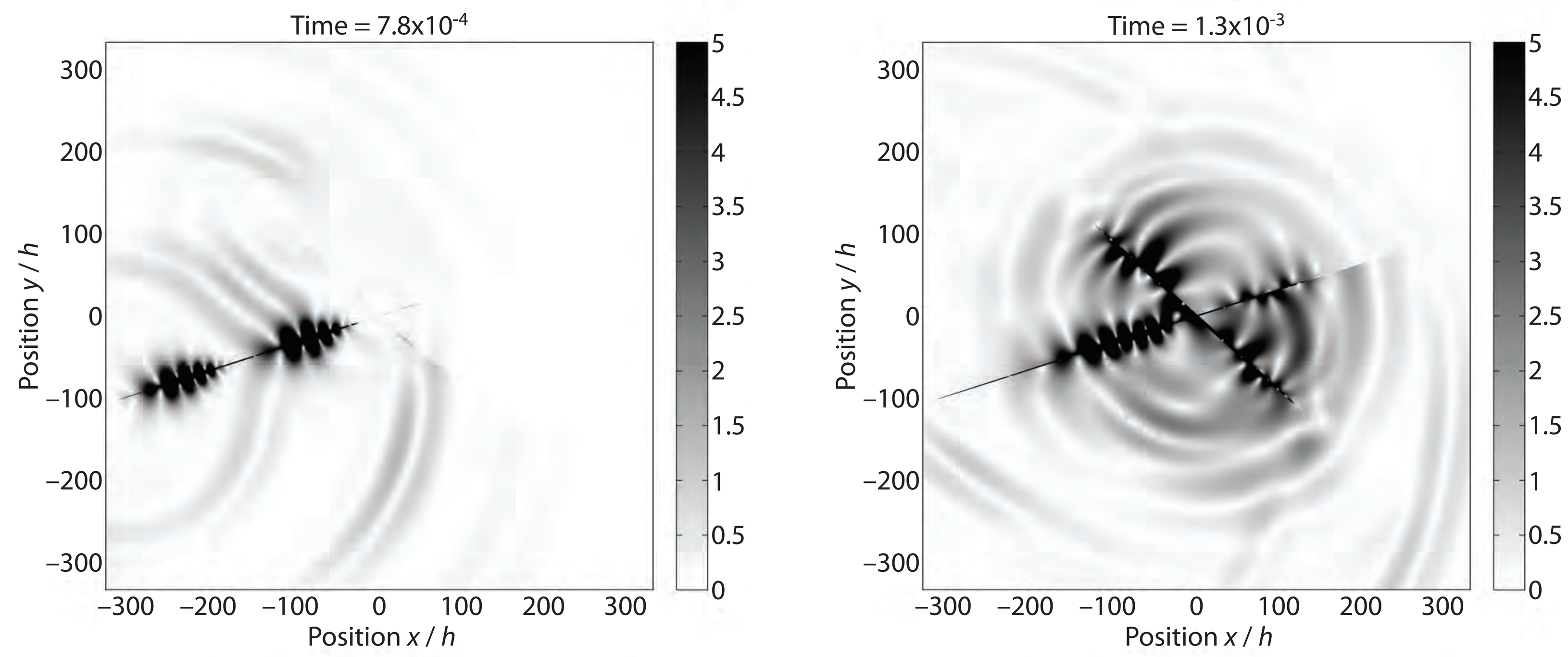
Reflection

Amplitude ratio |R| between reflected and incident SGWs. During numerical simulations incident and reflected SGW amplitudes are measured at indicated virtual receivers. The horizontal axis is the normalized bulk modulus of the fluid filling the crack.



Intersecting cracks

Two snapshots of the normalized absolute displacement of a SGW propagating along a crack that is intersected by a second crack. Both cracks have an elliptical shape and are filled with water. At the intersection point the incident SGW is split into four parts: 1) SGW that propagates straight ahead, 2) reflected SGW, 3) two SGWs that make a sharp turn and propagate along the second crack and 4) body waves emitted into the surrounding elastic rock.



Conclusions

The relatively strong reflection of SGWs at the tip of a crack enables them to fall into resonance when propagating back and forth many times along a crack. The emission of body waves makes the detection of SGW-related resonance signals possible.