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

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Understanding seismic wave propagation in fractured fluid-rock systems is important for estimating, for example, fluid properties or fracture densities from geophysical measurements. Stoneley guided waves have been used, for example, to explain long-period volcanic tremor signals or to propose potential methods for estimating fluid properties in fractured rocks. In this study, the finite element method is used to model two-dimensional wave propagation in a rock with a finite fluid-filled fracture (Figure 1). The surrounding rock is fully elastic with non-dispersive non-attenuating P- and S-waves. The fluid filling the fracture is elastic in its bulk deformation behavior but viscous in its shear deformation behavior. Therefore, only P-waves can propagate in the fracture, which are dispersive and attenuated. The fracture geometry is resolved in detail by the applied unstructured finite element mesh using triangles.
A Stoneley guided wave is a special wave mode that is bound to and propagates along the fracture with a much smaller velocity than all other waves in the system. In this study, the wave length of the Stoneley guided wave is two orders of magnitude larger than the thickness of the fracture. Its amplitude decreases exponentially away from the fracture, which makes the Stoneley guided wave difficult to detect already a relatively short distances away from the fracture. At the tip of the fracture the Stoneley guided wave is reflected (Figure 1). The amplitude ratio |R| between reflected and incident Stoneley guided wave is calculated from numerical simulations (Figure 2), which depend on the type of fluid filling the fracture (water, oil or hydrocarbon gas), the fracture geometry (elliptical or rectangular) and the presence of a small gas cap at the fracture tip. For an elliptically shaped fracture (aspect ratio of ellipse = 333) the amplitude ratio varies between 75% for oil and water and almost 100% for gas. Although the fracture thickness is two orders of magnitude smaller than the wave length, the shape of the fracture tip influences this ratio significantly. The amplitude ratio of a Stoneley guided wave at the tip of a straight water-filled fracture with a flat fracture tip is around 43%.
The part of the Stoneley guided wave that is not reflected is scattered at the fracture tip and emitted into the surrounding elastic rock as elastic body waves (Figure 1). For fully saturated fractures the radiation of these elastic body waves points in every directions from the fracture tip. In the presence of a small gas-cap at the tip of a fluid-filed fracture the radiation of the elastic body waves is strongly forward directed. The relatively strong reflection at the fracture tip enables the Stoneley guided wave to travel back and forth along a fracture several times before it looses too much of its initial energy. This leads to a periodic radiation of body waves at the fracture tip. The corresponding frequency can be low in relatively small fractures due to the small velocity of

Stoneley guided waves. The emitted elastic body waves may allow detecting Stoneley guided wave-related signals at distances away from the fracture where the amplitude of the Stoneley guided wave itself is too small to be detected.

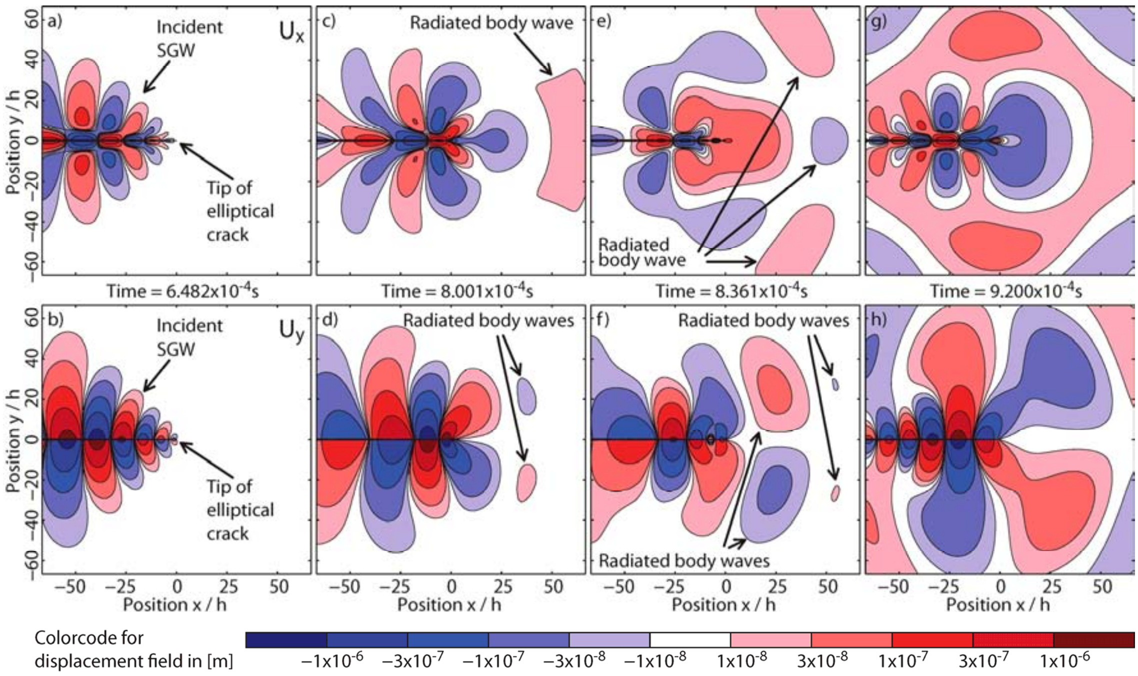

Figure 1: Snapshots of the 2D displacement field of a simulation of a Stoneley guided wave propagating along an elliptical crack filled with water. Upper panels show the horizontal component of the displacement field. Lower panels show the vertical component of the displacement field. Panels from left to right represent progressive points in time. The Stoneley guided wave is partially reflected at the crack tip and elastic P- and S-waves are emitted from the crack tip into the surrounding rock.

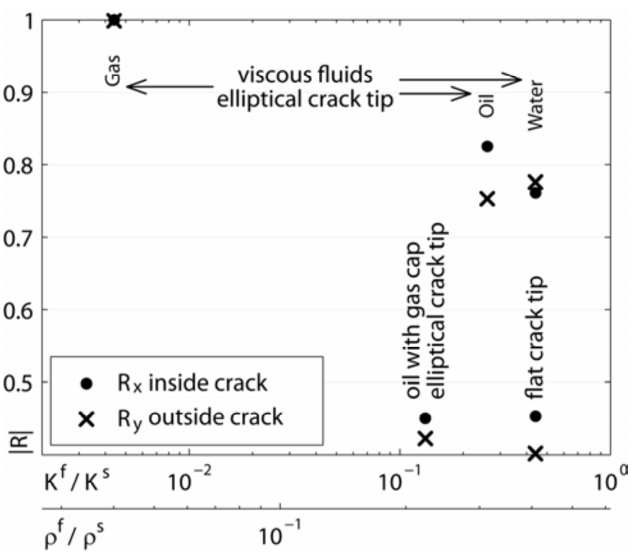

Figure 2: Absolute value of the amplitude ratio |R| between reflected and incident Stoneley guided wave of a Stoneley guided wave that is reflected at the tip of a crack. R_x is calculated from the horizontal displacement-time signals at eight receivers inside the crack. R_y is calculated from the vertical displacement-time signals at six receivers outside the crack. Values labeled "viscous fluids, elliptical crack tip" are derived from simulations of an elliptical crack fully saturated with the corresponding viscous fluid. Values labeled "flat crack tip" are derived from a simulation of a rectangular crack with a flat crack tip fully saturated with viscous water. Values labeled "oil with gas cap, elliptical crack tip" are derived from a simulation of an elliptical crack partially saturated with viscous oil and having a small gas cap at the crack tip.