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Reflection, radiation and attenuation of Stoneley guided waves in fluid-filled finite cracks

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Understanding wave propagation in fractured fluid-rock systems is important for estimating, for example, fluid properties or fracture densities from geophysical measurements such as ground motion. In this study, the reflection, radiation and attenuation of Stoneley guided waves in fluid-filled cracks is studied numerically. Stoneley guided waves have been used, for example, to explain long-period volcanic tremor signals or to propose potential methods for estimating the fluid properties in fractured rocks. However, direct numerical simulations of Stoneley guided waves in fluid-filled fractured rocks are rare. In this study, the finite element method (FEM) is used to model two-dimensional wave propagation in an elastic rock with an elliptically shaped finite crack (aspect ratio of length to thickness is 333.3) filled either with a viscous or inviscid fluid. The surrounding rock is fully elastic with non-dispersive P- and S-waves able to propagate without attenuation. The fluid filling the crack is elastic in its bulk deformation behavior but viscous in its shear deformation behavior. Therefore, only P-waves are able to propagate in the crack, which are dispersive and attenuated. The crack geometry, especially the crack tips, is resolved in detail by the applied unstructured finite element mesh using 7-node triangles. The presence of a fluid filled crack in the elastic rock gives rise to a so called Stoneley guided wave that is bound to and propagates along the crack walls with a much smaller velocity than all other waves in the system. Its amplitude decreases exponentially away from the crack and is therefore not detectable anymore at a certain distance. At the tip of the crack the Stoneley guided wave is reflected. The interference of incoming and reflected Stoneley guided waves leads to nodes (zero amplitude) and anti-nodes (maximum amplitude). One of the nodes is exactly at the crack tip. Therefore, the reflection is similar to a one-dimensional reflection of a wave propagating in a medium with lower impedance at the interface to a medium with higher impedance. At anti-nodes the amplitude is increased. However, the exponential decay away from the crack is stronger compared to an undisturbed Stoneley guided wave propagating along an infinite crack. Therefore, the reflection by itself does not enhance the detectability of Stoneley guided waves away from the crack. However, the reflection coefficient at the crack tip for cracks filled with common natural fluids (water, oil, hydrocarbon gas, magma) is around 0.8. In other words, a part of the Stoneley guided wave energy is transferred at the crack tip into the surrounding elastic rock in the form of P- and S-waves. The decay of these P- and S-waves away from the crack tip due to geometrical spreading is smaller than that of the Stoneley guided wave and they can eventually be detected. The relatively high reflection coefficient of 0.8 at the crack tip enables the Stoneley guided wave to travel several times back and forth along a finite crack before it lost too much of its initial energy. This leads to a periodic radiation of P- and S-waves at the crack tip each time the Stoneley guided wave is reflected. This periodic radiation can have very low frequencies in relatively small cracks due to the small velocity of Stoneley guided waves. Such low frequency signals may explain low frequency volcanic tremor, long-period volcanic earthquakes or low frequency tremor related to fractured hydrocarbon reservoirs.