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Phase velocity dispersion and attenuation of seismic waves due to trapped fluids in residual-saturated porous media

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Propagation of seismic waves in partially saturated porous media depends on various material properties, e.g. saturation, porosity, elastic properties of the skeleton, viscous properties of the pore fluids and, additionally, capillary pressure and effective permeability. If the wetting fluid is in a discontinuous state, i.e. residual-saturated configuration, phase velocities and frequency-dependent attenuation additionally depend on microscopical (pore-scale) properties such as droplet and/or ganglia size.

To model wave propagation in residual-saturated porous media, we developed a three-phase model based on an enriched continuum mixture theory capturing the strong coupling between the micro- and the macroscale. The three-phase model comprises the porous solid skeleton, a continuous fluid part and a discontinuous fluid part. The discontinuous part describes the movement of blobs/clusters of the wetting fluid and is based on an oscillator rheology. On the microscale, the oscillators are determined by their mass, damping and eigenfrequency. Amongst others, these properties depend on the microscopic geometry and surface tension. To embed the microscopic oscillators into a macroscopic poroelastic description of the non-wetting fluid and the skeleton, a scale bridging between both spatial scales is applied conserving density, eigenfrequency and damping. This homogenization approach accounts for the discontinuous character of the wetting fluid. Furthermore, probability density functions are used to describe the size distribution of different kinds of fluid clusters. The discontinuous fluid part is linked to the continuous solid phase by momentum exchange in the form of pinned or sliding oscillators. The non-wetting continuous fluid phase exhibits similar behavior as the poroelastic model introduced by Biot.

The final model delivers insight into the behavior of propagating waves on the macroscale, influenced by different properties of the microscopic oscillating fluid clusters. Furthermore, the dispersion relations allow for a comparison with continuous models, such as the Biot model, and for the calculation of characteristic values, which might be helpful for the comparison with experimental studies. We define a dimensionless parameter that determines if the overall motion of the residual fluid is dominated by oscillations (underdamped, resonance) or not (overdamped). Our results show that the residual fluid has a significant impact on the velocity dispersion and attenuation, no matter if it oscillates or not. For long wavelengths, our model coincides with the Biot-Gassmann equations. We show under which conditions and how the classical biphasic models can be used to approximate the dynamic behavior of residual-saturated porous media.