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 (Steeb et al., 2012) 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 considers a continuous and a discontinuous part (Figure 1). The continuous part, consisting of the porous solid skeleton and the continuous non-wetting fluid, exhibits similar behavior as the poroelastic model introduced by Biot (Biot, 1956). The discontinuous part describes the movement of blobs/clusters of the wetting fluid and is based on an oscillator rheology (Figure 1; Frehner et al., 2009, 2010; Steeb et al., 2012). In comparison with other three-phase models, the presented one (Steeb et al., 2012) accounts for the heterogeneity of the discontinuous fluid clusters by use of their statistically distributed inertia, eigenfrequency and damping effects. The heterogeneous and discontinuous distribution of the wetting fluid in form of individual blobs or fluid clusters is represented by a model-embedded distribution function of the cluster sizes. We define a dimensionless parameter, D, that determines if the overall motion of the residual fluid is dominated by oscillations (underdamped, resonance) or not (overdamped).

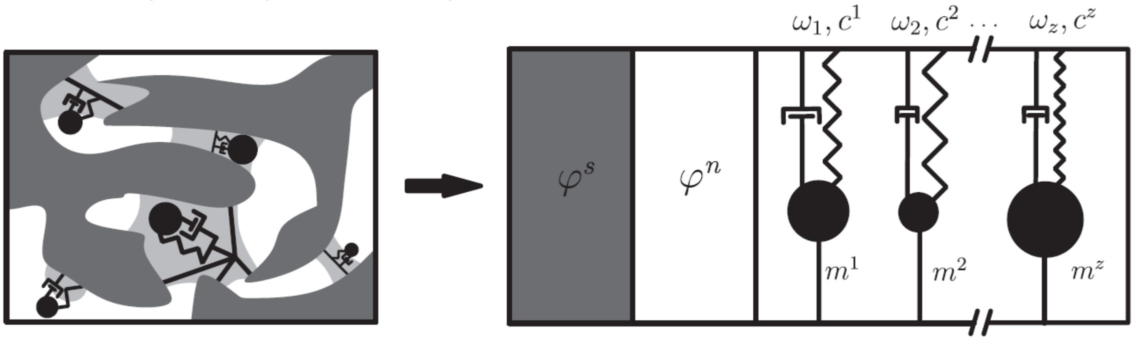

Figure 1. Upscaling from the heterogeneous pore-scale to an oscillatoric behavior of the wetting blobs with different eigenfrequencies and damping mechanisms at the macroscale (REV). The extended poroelastic model with the continuous solid skeleton φ^s, the continuous non-wetting phase φ^n and the discontinuous oscillators representing the wetting phase φ^w is depicted.

In the case of only a single fluid blob size (Figure 2), 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 small damping parameters (underdamped oscillations), a dispersion anomaly and a strong attenuation peak occurs around the resonance frequency. For large damping parameters (overdamped oscillations), the dispersion and attenuation curves are equal to the ones of the Biot's-theory, but shifted to higher frequencies. In the case of distributed fluid blob sizes (Figure 3), the same observation can be made comparing very narrow with wide size distributions. In Steeb et al. (2012), we show under which conditions and how the classical biphasic models can be used to approximate the dynamic behavior of residual saturated porous media.

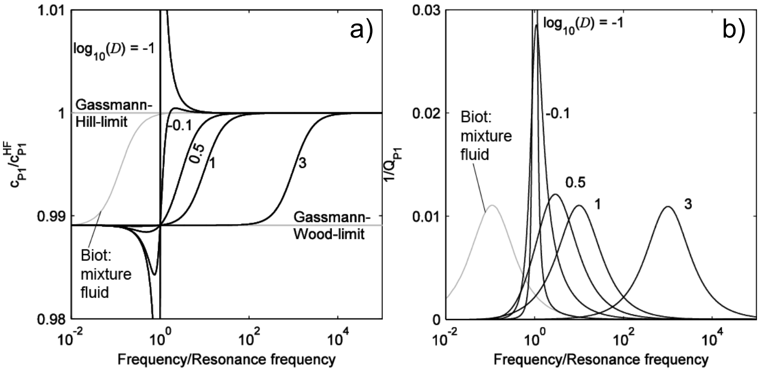

Figure 2. Frequency dependent phase velocity c_{P1} (a) and inverse quality factor $1/Q_{P1}$ (b) of the fast P-wave for different characteristic damping parameters D of the wetting fluid. The porous skeleton is a typical reservoir rock saturated with a continuous gas phase. The eigenfrequency of the blob is f_0=100 Hz.

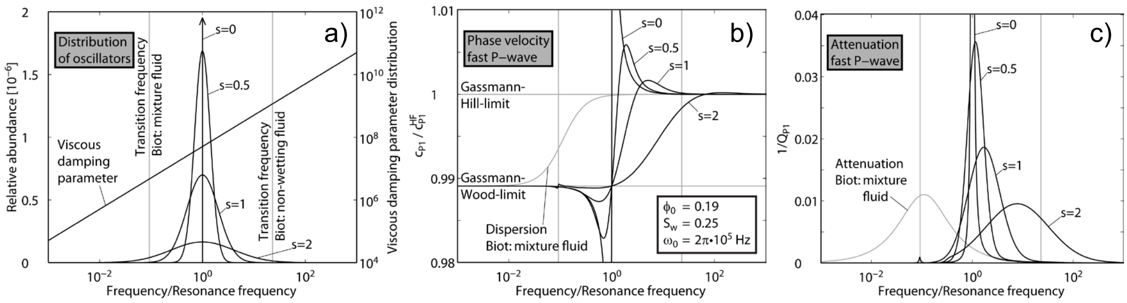

Figure 3. Frequency dependent phase velocity c_{P1} (b) and inverse quality factor $1/Q_{P1}$ (c) of the fast P-wave for different distributions of fluid blob sizes $c(\omega)$ and damping coefficients $\alpha(\omega)$ shown in a).

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