Effect of capillary pressure and contact angle hysteresis in a partially-saturated crack on low frequency moduli and attenuation

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Summary

Seismic wave induced fluid flow between heterogeneities in porous media is one of the major causes for elastic wave attenuation driven by viscous dissipation (*Muller et al.*, 2010). However, in a low frequency limit the work of capillary forces may dominate over the work of viscous forces during wave-induced two-phase fluid flow. The impact of capillary forces on low frequency elastic moduli and attenuation is not well understood. Seismic wave-induced deformations of the crack aperture induce displacements of the interface meniscus between immiscible fluids within a partially-saturated crack. The work of capillary forces during loading and unloading cycles of seismic wave propagation is irreversible, due to the contact angle hysteresis phenomenon. Using novel analytical solution for partially saturated crack (*Rozhko,* 2016) we calculate elastic moduli of representative elementary volume (REV) and demonstrate that loading and unloading bulk moduli are different due to the contact angle hysteresis phenomenon. Furthermore, we relate loading and unloading moduli to the change of seismic wave energy. We demonstrate that the change of seismic energy (Q-factor) driven by capillary forces can be either positive or negative. The negative attenuation, frequently observed during processing of VSP data, can be explained by our micro-mechanical model. Thermodynamically, negative attenuation is possible if energy of high frequency components is converted to energy of low frequency components.

Motivation

Negative attenuation means that the seismic amplitudes are increasing with depth. The negative attenuation is frequently observed during processing of VSP data: *Bouchaala et al.*, (2016) reported negative intrinsic attenuation values, observed even after removal of scattering effects in a fractured zone of a carbonate reservoir, partially-saturated with oil and water (located in Abu Dhabi, United Arab Emirates); *Matsushima* (2006) reported negative attenuation in methane hydrate-bearing sediments, located offshore Tokai, (central Japan); *Li et al.*, (2016) reported negative attenuation factors observed in conventional gas sandstone reservoir in the Red Folk Formation and in unconventional Barnet Shale reservoirs. Possible explanations for negative attenuation, suggested in literature are: geometrical focusing of seismic waves, scattering effects, ambient noise, spectral distortion by windowing, source conditions, geophone coupling, and the choice of receiver separation (*Matsushima,* 2006; *Bouchaala et al.,* 2016). These mechanisms may explain why the intrinsic attenuation can be locally negative. However, the experimental data of *Li et al.*, (2016) suggests that the negative attenuation is not a local (or focused) effect but can be observed over larger areas. Small negative values of seismic attenuation were also measured in the lab at low frequencies (1-200 Hz) for sandstone samples, saturated with different fluids (*Spencer and Shine*, 2016). However, authors attributed this "unphysical effect" to propagating errors in the calculations. The negative attenuation, observed by *Spencer and Shine* (*2016*) is small because only fundamental frequency (without overtones) were applied to the sample, while thermodynamically, negative attenuation of fundamental frequency is possible if energy of overtone frequency is converted to the energy of fundamental frequency.

Model

Our theoretical model (Fig. 1) is based on a recently published analytical solution for stresses and displacements around a partially-saturated crack (Rozhko, 2016). The initial geometry of the crack is approximated by an elliptical cavity. The wetting phase occupies the crack tips, while the non-wetting phase occupies the central part of the crack. The curvature of the interface meniscus defines the capillary pressure, which is a pressure difference between non-wetting and wetting fluid phases. The final spindle-like cross-section of the crack is calculated analytically by two-way coupling of the capillary pressure with the deformation of crack aperture (Rozhko, 2016).

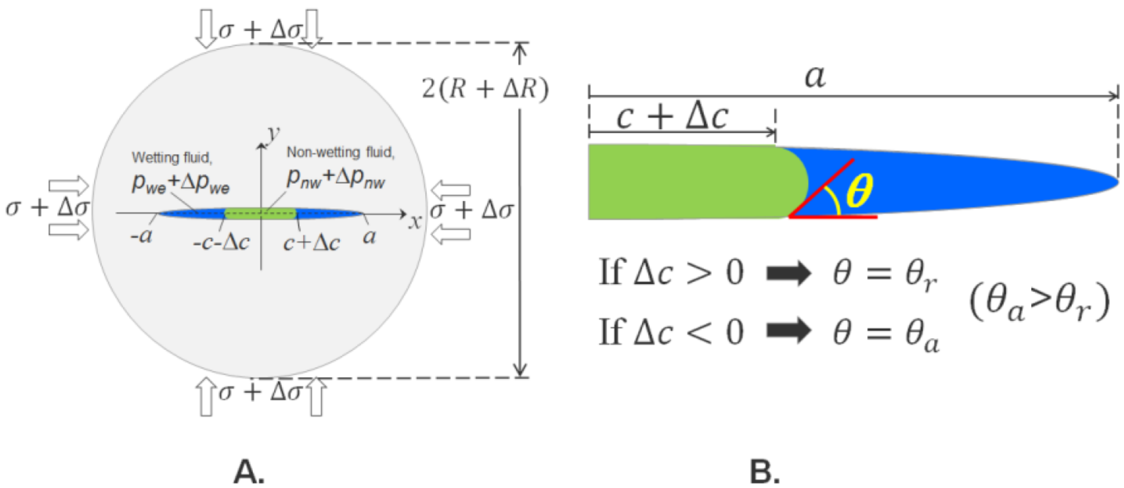

Figure 1 A: *Perturbation of the far-field total stress ($\Delta\sigma$) along the external boundary of REV, during seismic wave propagation.* ***B***: *The contact angle of the wetting phase on the crack surface (θ) during displacement of the interface meniscus, depends on the direction of the displacement; θ_a and θ_r are advancing and receding contact angles ($\theta_a > \theta_r$).*

Results

In the low frequency limit, there is sufficient time for the pore fluid to flow and eliminate wave-induced pore-pressure perturbations (*Mavko et al*., 2009), *i.e.* perturbations of the far-field total stress will not change fluid pressure in the wetting and non-wetting fluid phases inside the crack. Due to deformation of the crack aperture the perturbation of crack saturation is not negligible. Therefore, perturbations of effective pressure inside the crack are not zero in the low frequency limit, due to change of crack saturation. The maximum impact of stress perturbation on the change of crack saturation is predicted for the point where the capillary pressure of the crack reaches its minimum value at $Swe<1$ (Fig. 2).

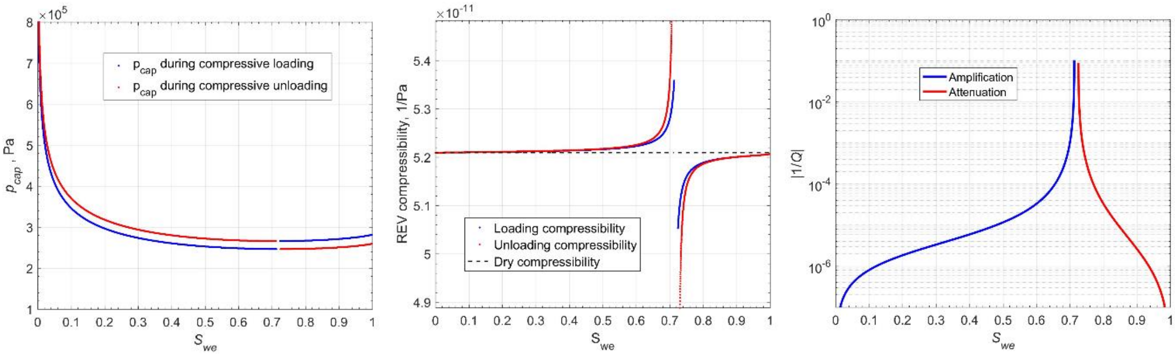

***Figure 2 Left**: Capillary pressure - saturation curves of partially saturated crack during compressive loading (blue curve) and during compressive unloading (red curve). The top curve corresponds to the receding contact angle value, while the lower curve corresponds to advancing contact angle. Capillary pressure curves are non-monotonic function of saturation and reaches its minimum value at Swe<1. **Middle**: Effect of capillary pressure on low frequency compressibility, blue and red curves show compressibilities during loading and unloading cycles; compressibilities are different due to contact angle hysteresis. Discontinuity of compressibility coincides with minimum of capillary pressure at Swe<1. Dashed black curve shows REV compressibility with dry-crack. **Right**: $|1/Q|$- factor vs wetting phase saturation of the crack. Blue curve shows negative attenuation, while red curve shows positive attenuation. A pick value coincides with minimum of capillary pressure at Swe<1.*

Conclusions

In this work, we presented a new micromechanical model for calculation of low frequency elastic moduli and seismic energy attenuation driven by capillary forces during wave-induced two-phase fluid flow between crack and matrix. Non-zero work of capillary forces during loading and unloading cycles is due to a contact angle hysteresis phenomenon. The model shows that in the low frequency limit wave-induced pore-pressure perturbations in the wetting and non-wetting phases are zero, while perturbations of crack saturation are not zero. Thus, perturbations of effective pressure inside the partially-saturated crack are not zero. This affect compressibilities of REV, which are different during loading and unloading cycles due to contact angle hysteresis phenomenon. Micromechanical model predicts that both positive and negative attenuation Q-factors are possible, where the negative attenuation is frequently observed during processing of VSP data from partially-saturated reservoirs. Thermodynamically, a negative attenuation is possible if energy of high frequency is converted to the energy of low frequency.

References

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