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Effect of Viscous Cross Coupling between two Immiscible Fluids on Elastic Wave Propagation and Attenuation in Unsaturated Porous Media

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A central issue in the theoretical treatment of a multiphase system is the proper mathematical description of momentum transfer across fluid-solid and fluid-fluid interfaces. Although recent studies have advanced our knowledge on modeling the coupling behavior between a porous framework and the fluids permeating it, the effect of viscous resistance caused by two-fluid flow on elastic wave behavior in unsaturated porous media still remains unaddressed. In the present study, we generalize the theory of dynamic poroelasticity to incorporate viscous cross coupling arising from the velocity difference between two adjacent fluids for examining the dynamic behavior of fluid flow in deformable porous media related to harmonic wave perturbation. The corresponding dispersion relations that characterize three compressional waves and one shear wave are precisely formulated, with the coefficients featuring all elasticity, inertial coupling, and viscous coupling parameters, for describing how wave number changes as excitation frequency is stipulated.
To evaluate quantitatively this as-yet unknown effect, numerical simulations are implemented to solve the dispersion relations for Columbia fine sandy loam bearing an oil–water mixture with respect to three representative wave excitation frequencies. Our results show that the phase speed and attenuation coefficient of the third compressional wave which has the smallest speed is strongly sensitive to the presence of viscous cross coupling, as expected for this wave being attributed primarily to the out-of-phase motion of the two pore fluids. Viscous cross coupling also exerts an impact on the attenuation coefficient of the shear wave and the first compressional wave whose speed is greatest, which exhibits two opposite trends at different ranges of low and high water contents. A sensitivity analysis is further conducted to provide information on the importance of the coupling parameter, revealing that the effect becomes more significant as the coupling is stronger.