Analytical decoupling of poroelasticity equations for acoustic wave propagation and attenuation in a porous medium containing two immiscible fluids

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Poroelasticity theory has become an effective and accurate approach to analyzing the intricate mechanical behavior of a porous medium containing two immiscible fluids, a system encountered in many subsurface engineering applications. However, the resulting partial differential equations in the theory intrinsically take on a coupled form in the terms pertinent to inertial drag, viscous damping, and applied stress, making it difficult to obtain closed-form, steady-state analytical solutions to boundary-value problems except in special cases. In the present paper, we demonstrate that, for dilatational wave excitations, these partial differential equations can be decoupled analytically into three Helmholtz equations featuring complex-valued, frequency-dependent normal coordinates that correspond physically to three independent modes of dilatational wave motion. The normal coordinates in turn can be expressed in the frequency domain as three different linear combinations of the solid dilatation and the linearized increment of fluid content for each pore fluid, or equivalently, as three different linear combinations of total dilatational stress and two pore fluid pressures, representations which are applicable to strain-controlled and stress-prescribed boundary conditions, respectively. Numerical calculations confirm that the phase speed and attenuation coefficient of the three dilatational waves represented by the Helmholtz equations are exactly identical to those obtained previously by numerical solution of the dispersion relations for dilatational wave excitation of a porous medium containing two immiscible fluids. Thus dilatational wave motions in unsaturated porous media subject to suitable boundary conditions can now be accurately modeled analytically.