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Modelling the effects of saturation hysteresis on the seismic signatures of partially saturated heterogeneous porous media

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Partially saturated geological formations are of interest in a wide variety of scientific scenarios and practical applications throughout the Earth, environmental, and engineering sciences. Experimental evidence indicates that the spatial distribution of immiscible pore fluids in such environments is determined by the flow history. Thus, hysteresis effects need to be considered to allow for an adequate seismic characterization of partially saturated media. To date, most works concerned with modelling the effective seismic properties of partially saturated rocks either disregard the effects of saturation hysteresis or account for them employing oversimplified methodological approaches. This, in turn, can lead to erroneous interpretations of the corresponding seismic signatures. In this work, we present a novel methodology that allows to compute seismic attenuation and dispersion due to mesoscopic wave-induced fluid flow (WIFF) accounting for hysteresis effects and considering realistic saturation patterns. For this purpose, we employ a pore-scale model that represents a porous medium as a bundle of constrictive capillary tubes with a fractal pore size distribution. This approach has the advantage of providing closed analytical expressions for the porosity, the permeability, and the primary drainage and imbibition capillary pressure-saturation curves for a wide range of pertinent scenarios. By assuming that the different regions of a heterogeneous rock sample can be locally described by this constitutive model and considering a set of capillary equilibrium states, we obtain the saturation fields associated to drainage and imbibition cycles. Then, applying a numerical upscaling procedure, based on Biot's theory of poroelasticity, we compute seismic attenuation and dispersion curves in response to mesoscopic WIFF. Our results indicate that saturation hysteresis effects can have a significant influence on the seismic signatures of partially saturated porous media. The numerical simulations also show that the pore-scale characteristics of a given porous medium, such as the pore-throat to pore-body size ratio, can greatly influence the hysteretic behavior of the attenuation and dispersion curves. The proposed approach thus offers the perspective of fundamentally improving our understanding of the WIFF phenomenon in partially saturated heterogeneous rocks in general and its relationship with hysteresis effects in particular.