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Limits of applicability of the Richards equation from scaling capillary, gravity and viscous forces in unsaturated porous media

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Interplay between capillary, gravity and viscous forces in unsaturated porous media gives rise to a range of complex flow phenomena that affect wetting front morphology, stability and dynamics of drainage. Different fluid distributions for similar average phase content may affect macroscopic transport properties of the unsaturated medium. Several unifying concepts emerge from the scaling relationships of Podgorski et al. [PRL 2001] in which gravitational force in excess of capillary pinning force scales linearly with the viscous force, and analyses of Meheust et al., [PRE 2002] for flow morphology using dimensionless Bond and Capillary numbers and their difference (the generalized Bond number). Evidence supports the generality of such scaling relationships for a broad range of flow regimes and for predictions of drainage front morphology (at pore to sample scales). Based on limited experimental support, the scaling relationships may be used to define conditions for onset of unstable flows leading to enhanced liquid and gas entrapment, and provide a basis for delineation of a tentative value of Bo$\sim$0.05 as an upper limit of applicability of the Richards equation and similar continuum-based models.