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Front instability and energy of the free surface

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In recent years, there has been a proliferation of research devoted to the formation of preferential flow paths occurring without macroscopic heterogeneity of the porous media. DiCarlo (2013) points out the connection between "overshoot" and the front instability. Extension of the standard Richards equation is required to capture this phenomenon. In most of the improvements, interfacial phenomena as the triple line at the front are considered. For instance, velocity dependent contact angle (Wang et al., 2013) or contact angle hysteresis (Rätz and Schweizer, 2012) allow to simulate successfully the instability. Another approach proposed by Cueto-Felgueroso and Juanes (2009) introduces a macroscopic surface tension related to the existence of the water/air interface. As previously, the simulation of an advancing front displays physical looking fingering displacements.
The goal of this contribution is to better understand the role of the different surface energies in the emergence of the front instability. We propose a model involving both the macroscopic surface tension and the soil wettability. This latter allows to define a contact angle and possibly hysteresis using heterogeneous wettability (Beltrame et al., 2011). Therefore, we employ the phase field approach developed by Felgueroso and Juanes, 2009 to which we add a free energy term corresponding to the wettability: a disjoining or conjoining pressure resulting from effective molecular interactions between the substrate and the free surface (DeGennes, 1985). The difference with the classical suction pressure is the hydrophobic behavior for ultra-thin film (small water saturation). Such a water repellency was recently estimated in the soil (Diamantopoulos et al. 2013).
Stability analysis of an advancing front in an uniform porous media shows that macroscopic surface tension and wettability may independently produce the instability growth. In contrast, for a front stopping when reaching the layers interface of stratified media, the wettability is required for the emergence of instability. Then, finger flow crosses over the discontinuity. However, the non-local term (due to the surface tension) scales the characteristic finger width. Therefore, this study brought to light that the fingers flow modeling requires both surface energies related to wettability and macroscopic surface tension.

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