Title

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The unsaturated hydraulics of soils, sediments and rocks encompass a wide range of scales, properties, and processes, making it difficult to reliably predict the behavior of one type of medium based on relations developed for another. Although the unsaturated hydraulics of fine to medium textured granular media has been rather thoroughly developed, especially in terms of bulk properties, application of some basic soil physics concepts to unsaturated fractured rocks have often not yielded reliable predictions without introducing additional adjustable parameters. This failure indicates that some key phenomena and processes cannot be arbitrarily transferred from one scale to another. We have been examining the unsaturated hydraulics of sands, gravels, and rocks in an attempt to better understand scaling relations and limitations. This presentation summarizes recent finding in 3 areas: (1) general limits to classical capillary scaling, (2) surface roughness constraints on capillary film flow, and (3) scaling of fast flow paths in low storage capacity rocks.

Hysteresis in the relation between water saturation (S) and matric potential (ψ) is generally regarded as a basic aspect of unsaturated porous media. However, since hysteresis depends on whether or not capillary rise occurs at the grain-scale, this criterion can be used to predict combinations of grain-size (λ), surface tension (σ), fluid-fluid density differences ($\Delta\rho$), and acceleration (a) that prevent hysteresis. Vanishing of $S(\psi)$ hysteresis was predicted to occur for $\lambda > 11$ mm, for water-air systems under the acceleration of ordinary gravity, based on Miller-Miller scaling and Haines' original model for hysteresis. The Haines number, Ha, is proposed as a dimensionless number useful for separating hysteretic ($Ha < 15$) versus nonhysteretic ($Ha > 15$) behavior. Disappearance of hysteresis was tested through measurements of drainage and wetting curves of sands and gravels. For λ up to 7 mm, hysteresis loops remain well defined. At $\lambda = 9$ mm, hysteresis is barely detectable. At $\lambda \approx 11$ mm, hysteresis loops are difficult to reproduce, having energy offsets comparable to measurement uncertainties. For $\lambda > 13$ mm, hysteresis is not observed. The influence of σ was tested through measurements of moisture retention in 7 mm gravel, without and with a surfactant (sodium dodecylbenzenesulfonate, SDBS). At $\lambda = 7$ mm, the ordinary water system ($\sigma = 71$ mN m^{-1} and $Ha = 7$) exhibited hysteresis, while the SDBS system ($\sigma = 27$ mN m^{-1} and $Ha = 18$) did not. These experiments prove that hysteresis is not a fundamental feature of unsaturated porous media. This finding is important to be aware of in studies of unsaturated flow in fractures, for example, when using a centrifuge to conduct experiments at higher accelerations than that of gravity at the earth surface.

Preferential flow paths for unsaturated flow in fractured rocks remain an outstanding challenge to understand and predict. The balance between gravity and capillarity is critical to this problem, over a wide range of length scales. How well dispersed or localized will flow paths be? The approach we take on this problem starts at the scale of fracture surface roughness, along individual fractures. At this scale, a number of flow path configurations can accommodate any specific boundary condition that preserves near-zero matric potentials. We show that surface topography, as described by root mean square roughness or similar parameters, can often constrain film transmissivity relations, but is inadequate for predicting film flow, even when supplemented with information on surface wettability. This limitation is analogous to the more familiar inability to predict fracture transmissivity, saturated or unsaturated, solely from information on average aperture.

At the larger scale of an unsaturated fracture network, models for flow paths can largely ignore capillarity. The physical basis for this gravity-only approximation in low storage capacity rocks is presented, along with supporting experimental evidence. We concluded with presently some models that fail and some that succeed in predicting unsaturated flow path distributions.