Flow and Transport in Water Films

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Conceptual models for water flow and transport in fractured rock and soils commonly assume that potential conduits are either completely desaturated or saturated at the fracture aperture scale and pore-scale. Models based on such concepts assume that in partially saturated fractured rock and soils, flow takes place through an interconnected network of saturated segments. We have shown that such models for flow in partially saturated fractures are generally incorrect because they ignore in controlling influence of film flow. Flow along unsaturated fractures is generally controlled by water films on rough fracture surfaces which provide hydraulic continuity between locally saturated aperture segments, and which typically provide higher hydraulic resistance than locally saturated aperture segments. In this presentation, we first briefly review our previous work on film flow, then provide an update summarizing our recent results. These include (1) quantifying the range conditions (rock permeability, matric potential, and fracture aperture) under which film flow can be important, (2) several ways to measure film hydraulic diffusivities, and (3) examples of vadose zone chemical transport along films.

The range of conditions under which film flow in fractured rock can occur is generally bounded by two limits, saturation of the rock matrix at the fracture surface, and saturation of the fracture aperture. It is useful to link both of these limiting conditions to the local potential energy of water, specifically the matric potential. The lower critical matric potential at which the pores in the rock surface become effectively saturated can be approximately associated with the air-entry value. For rock with Miller-similar matrix properties, air-entry matric potentials scale with the inverse square-root of rock permeability. Although this scaling represents an ideal limit, a survey of a wide range of materials has indicated that such a permeability correlation predicts lower critical (air-entry) potentials within one order of magnitude. From capillary considerations, the magnitude of the upper critical matric potential (associated with local aperture saturation) is inversely related to the local aperture size. An evaluation of these two limits reveals that film flow can be important in vadose zone rock with permeabilities less than about 1E-14 m2, and with apertures larger than 10 micrometer. It is important to recognize that such conditions are common, hence film flow in the vadose zone can be quite common.

Transient film flow experiments have been performed in order to observe rates of film advance and determine film hydraulic diffusivity relations. Experimental procedures and methods for analyzing data generally follow from previously established soil physics techniques which are routinely applied in studies of unsaturated porous media flow. Calculated film hydraulic diffusivities based on two independent techniques, pressure plate outflow and transient imbibition, are in good agreement. The importance of fracture surface roughness and wettability on film flow was clearly evident in these transient experiments.

Chemical transport during film flow was investigated in a column packed with synthetic soil aggregates. Unsaturated flow and transport of Cr(VI) through this column was monitored with an x-ray fluorescence microprobe (National Synchrotron Light Source, beamline X26A). The x-ray microprobe mapping showed that Cr was primarily distributed along aggregate edges bounding unsaturated film flow paths. Micro-XANES spectra showed partial reduction of Cr(VI).