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MECHANISMS FOR FAST FLOW IN UNSATURATED FRACTURED ROCK

Tetsu K. Tokunaga and Jiamin Wan
Earth Sciences Division, E.O. Lawrence Berkeley National Laboratory
Berkeley, California, U. S. A.

Abstract

Although fractures in rock are well-recognized as pathways for fast percolation of water, the possibility that fast flow could occur along unsaturated fracture pathways is commonly not considered in vadose zone hydrology. In this study, two mechanisms for fast flow along unsaturated fractures were investigated, film flow and surface zone flow. The importance of fracture surface roughness was demonstrated through experiments conducted on ceramic blocks having simple surface topographies. Those experiments showed that film flow on fracture surfaces is largely due to flow along continuous surface channels which become water-filled at near-zero matric (capillary) potentials. The second mechanism, surface zone flow, is important when the permeability of the rock along fractures (fracture skin) is significantly greater than that of the bulk rock matrix. Surface zone fast flow was demonstrated through water imbibition (sorptivity) experiments. These mechanisms help explain observations of rapid solute transport in unsaturated subsurface environments.

Introduction

Important segments of the hydrologic cycle in arid and semi-arid regions remain incompletely understood, including processes by which water percolates through thick regions of unsaturated fractured rock. Rapid migration of solutes through some portions of deep vadose (unsaturated) zones has recently been observed [Nativ et al., 1995; Fabryka-Martin, 1996]. Such findings clearly show preferential water flow along a fraction of potentially conductive pathways, and disequilibrium between fractures and the rock matrix. When such fast flow processes are observed in polluted sites or sites being considered for waste storage, contamination of underlying groundwater becomes an important concern. Most conceptual models for flow and transport in unsaturated fractured rock require high fracture saturations in order to permit flow through fractures. Such models envision small regions of fractures as being either fully saturated or desaturated (Fig. 1a), with the condition for local fracture saturation essentially based on aperture-capillarity considerations [Wang and Narasimhan, 1985; Pruess and Tsang, 1990]. In such conceptualizations, local segments within a fracture are either saturated (conductive) or dry (nonconductive), such that continuous saturated pathways within fractures are required to sustain fast flow. However, observations of rapid transport through unsaturated fractured rock often are not associated with evidence for such continuous, saturated flow pathways. Until recently, transient pulses of locally highly saturated fracture flow during episodic, high intensity rainfall events provided the only explanation for fast flow through fractured vadose zones [Nitao and Buscheck, 1991; Wang et al., 1993]. In this paper, we present two other mechanisms which can explain fast flow along unsaturated fractures. We show that in unsaturated flow through rock of low matrix permeability, rough fracture surfaces can support fast film flow and fast flow within high permeability surface zones (Fig. 1b).

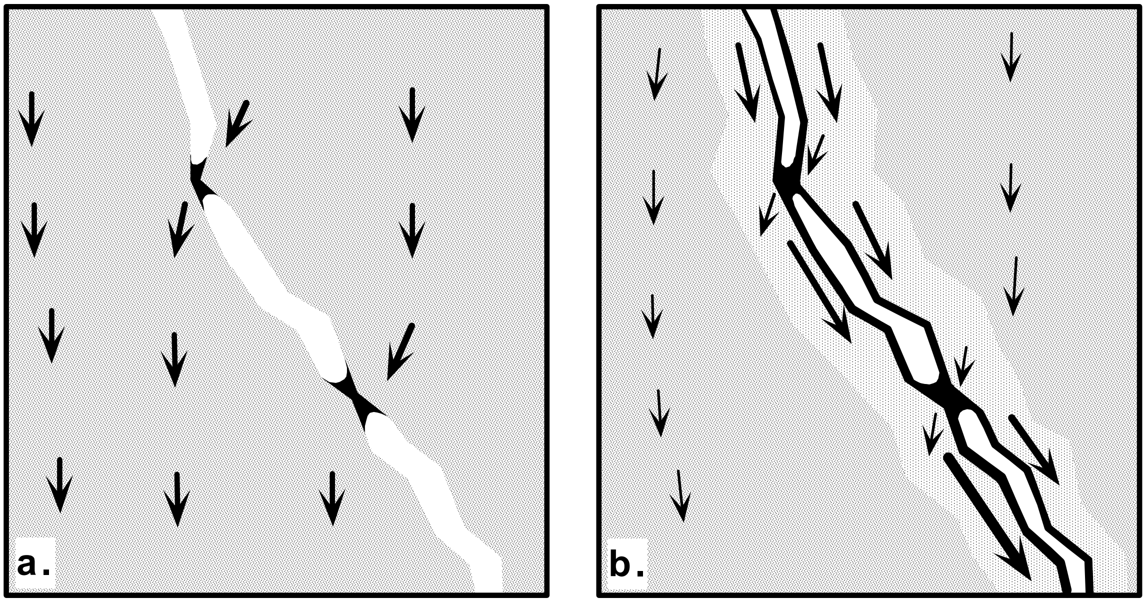

Figure 1. Contrasting the conventional aperture-based model (a), and the surface zone and film models (b) of water flow in unsaturated fractured rock. Note that high fracture saturations are generally needed in the conventional model before significant flow can occur along the fracture plane. When the fracture surface zone has a higher permeability than the underlying matrix rock, and/or when continuous transmissive films span unsaturated regions of fractures, fast flow of water can occur along partially saturated fractures.

Film flow along fracture surfaces has been recently identified, and shown to depend on surface roughness and the matric (capillary) potential [Tokunaga and Wan, 1997]. Water film thickness can build up along fracture surfaces when the matric potential is high enough to sustain effectively saturated conditions in the immediately underlying matrix. As matric potentials increase (towards zero), water film thicknesses expand along fracture surfaces by first filling finer scale roughness features, and progressively filling coarser roughness features. The transmissivity (volumetric flux per unit length transverse to flow, under a hydraulic head gradient of unity) of such films increases with film thickness, and supports fast gravity-driven flow. In the earlier study [Tokunaga and Wan, 1997], the influence of surface roughness on flow was only qualitatively identified through comparing the very rapid advance of a dye tracer down a natural rough fracture surface relative to its insignificant movement down an adjacent polished flat surface. In the present study, the influence of surface roughness on film flow is more quantitatively evaluated through experiments on surfaces with simple topography.

Another mechanism which can support fast flow along unsaturated fractures occurs in fracture coatings and fracture surface zones which have undergone permeability-enhancing alterations. When the permeability of the fracture surface region is significantly greater than that of the underlying matrix, water will flow preferentially along the fracture surface (Fig. 1b). Previous studies have examined the influence of the fracture surface zone, or fracture skin, on matrix imbibition of water from fractures [Thoma et al., 1992; Chekuri, 1995]. Such studies have addressed the importance of permeability contrasts in controlling rates of water flow from fractures into rock. It can be equally important to consider the influences of permeability contrasts on flow along the fracture plane. From this perspective, it is interesting to note that contrasts in permeability between the surface zone and underlying matrix promote flow along the fracture plane, regardless of which region is higher in permeability. When the surface zone is very low in permeability, flow is confined within the fracture. When the surface zone has a very high permeability relative to the underlying matrix, fast flow can occur along the fracture plane, within this fracture skin. We will consider this possibility in the second portion of this study, since it too can yield fast flow along unsaturated fractures.

Materials and Methods

In order to more quantitatively examine the effects of surface roughness on film flow, experiments were conducted on water-saturated ceramic blocks with simple V-channel surface corrugations. Use of systems with such simple geometries for examining flow along rough surfaces follows from the long history of conceptual and physical models of flow in porous media which are based upon bundles of capillary tubes. The 70 mm (width and height) by 10 mm (average thickness) blocks were cut from porous ceramic (0.1 MPa air-entry, Soilmoisture Equipment Corp., Santa Barbara, CA). Individual ceramic blocks were prepared with (i) flat, polished surfaces, (ii) V-channels aligned with the downwards flow direction, (iii) V-channels aligned transverse to the flow direction, and (iv) V-channels both parallel and transverse to the flow direction. Two sets of tensiometer ports (2.9 mm ID) were drilled into each block, centered at 7.0 mm vertical distances from the lower and upper surfaces. The blocks were vacuum-saturated with water prior to beginning flow experiments. Each block was tested individually. Tensiometer lines connected the 4 ports to individual pressure transducers (Validyne DP15-22, Northridge, CA). The effective hydraulic conductivity versus matric potential relations for these ceramic blocks were determined by adjusting flow rates and boundary potentials to establish unit hydraulic head gradients at specific values of the matric potential, in the manner described previously [Tokunaga and Wan, 1997]. We define the effective hydraulic conductivity as the flux through both the matrix and along surfaces under a unit hydraulic head gradient, per unit horizontal cross-sectional area normal to flow.

Experiments on surface zone fast flow were conducted on a sample of welded tuff bounded by a fracture surface (Topopah Spring Tuff, Yucca Mountain, NV), and a rhyolite bounded by a cooling joint surface (Owens River Gorge, Mono County, CA). Qualitative observations of surface zone fast flow were obtained through experiments in which water entered the sample block through both the surface zone and bulk rock matrix (Fig. 2a). More quantitative evaluation of surface zone flow was obtained by conducting imbibition (sorptivity) tests with water entering through the surface zone, then into the bulk rock matrix (Fig. 2b). A variety of similar methods have been used by other researchers [Peters et al., 1987; Chekuri, 1995; Humphrey et al., 1996], although not for purposes of identifying fast flow along fracture surfaces. The initially air-dry rock sample is suspended from the bottom hook of an electronic balance by a wire. The suspension wire is adjusted such that the lower surface of the rock is horizontal (within < 1 mm). The sample and water pan reservoir are contained within a chamber (desiccator box) to minimize evaporative water losses. The hole on the top surface of the chamber provides about 1 mm radial clearance between the chamber ceiling and the suspension wire. At time-zero, the free water surface is place in contact with the bottom surface of the rock by raising the chamber with the jack stand. The cumulative apparent imbibition mass indicated by the electronic balance is recorded as a function of time. The apparent imbibition mass is corrected for the small decline in the reservoir water level, normalized to the horizontal surface area, and expressed as cumulative imbibition (mm). Experiments were done for imbibition through the fracture surface, and for imbibition through "matrix only" samples. The "matrix only" samples included both blocks of the same rock without a fracture surface, and the blocks with fracture surfaces. In the latter case, the fracture surface is oriented upwards such that imbibition occurs directly into the matrix. Samples were oven-dried (105 ˚C, 24 h) after each test, and rerun to test reproducibility.

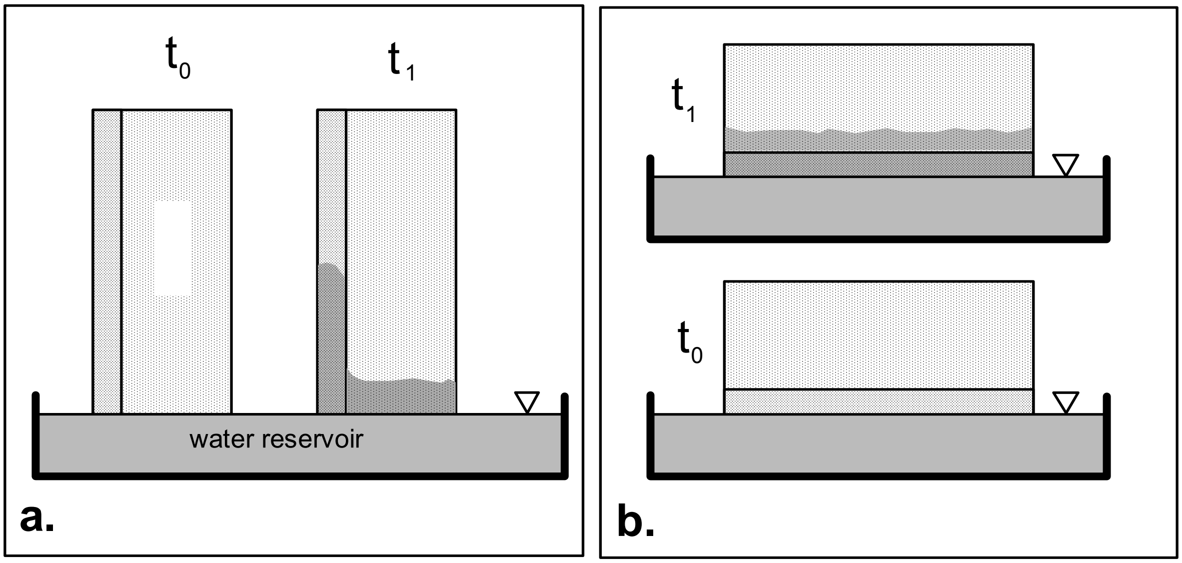

Figure 2. Orientation of fractured rock in the two type of imbibition experiments. (a) With the sample oriented with the fracture surface vertical, perpendicular to the free water surface, imbibition can occur simultaneously through the fracture surface zone and the bulk matrix. (b) When the sample is oriented with the fracture surface faced downwards and parallel to the free water surface, imbibition occurs first through the fracture surface zone, then into the bulk matrix.

Results and Discussion

Film Flow

Comparisons of effective hydraulic conductivities for the flat surface ceramic and the ceramic with V-channels aligned with the flow direction show very large differences at matric potentials very close to zero (Fig. 3). The effective hydraulic conductivity of the flat-surface ceramic remains constant, and equal to the hydraulic conductivity of the matrix over nearly the full range of matric potentials tested, with relatively small increases at matric potentials very close to zero. The effective hydraulic conductivity of the V-channel ceramic shows up to 4 orders of magnitude increases in the near-zero matric potential range. The transmissivity of this V-channel sample becomes as large as 10^{-5} m^2 s^{-1}, corresponding to average velocities up to 3 km d^{-1} within channels. Differences between these laboratory measurements and a linear combination of the saturated matrix hydraulic conductivity and predicted V-channel fluxes based on an approximate solution by Romero and Yost (1996) are within 100 Pa (10 mm) of matric potential and an order of magnitude in effective hydraulic conductivity (Fig. 3). The effective hydraulic conductivity function of the ceramic with channels transverse to flow was similar to that of the flat surface, despite the fact that pendular water thicknesses built up to nearly fill the 1.0 mm deep channels at near-zero matric potentials. This result demonstrated the very high hydraulic resistance encountered for flow transverse to ridge features. Finally, experiments on the ceramic block with channels in both transverse and parallel orientations yielded results which were very similar to those on the block with only channels aligned with the flow direction. These results demonstrate the importance of surface roughness and surface tortuosity in film flow.

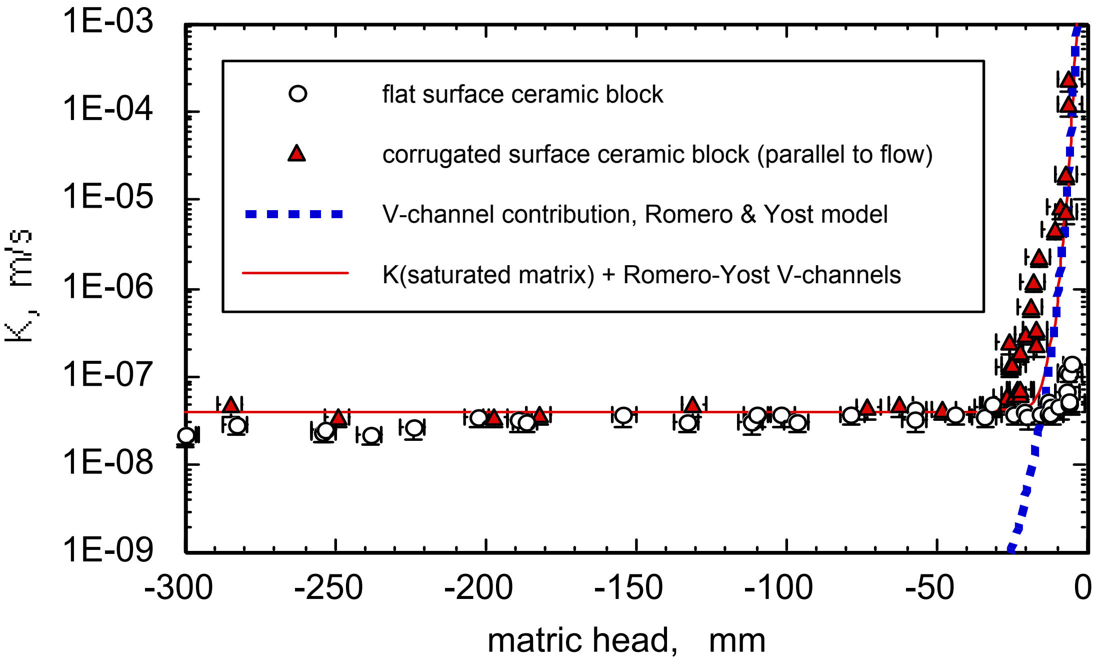

Figure 3. Effective K versus matric potential for the flat surface ceramic block and V-channel surface ceramic block with channels aligned with the downwards flow direction. Also shown are predictions based upon the Romero-Yost model.

Fracture Surface Zone Fast Flow

Fast flow along some fracture surface zones is qualitatively evident in observations of wetting front advance parallel to the fracture plane, as shown for upwards water imbibition into a welded tuff with a fracture coating (Fig. 4a). This phenomenon is also observed in similar imbibition experiments on a rhyolite with a cooling joint fracture surface (Fig. 4b). The former example shows much greater wetting within the silicate fracture coating than into the underlying welded tuff matrix. The latter example shows more rapid wetting in the microfractured cooling joint surface zone rather than in the matrix rock.

Figure 4. Upwards imbibition of dyed water from a lower boundary maintained at a matric potential of -80 Pa. (a) Imbibition into initially dry Topopah Spring Tuff (welded), showing fast flow within the fracture coating (t = 25 minutes, reference marks at 5 mm intervals). (b) Imbibition into initially dry rhyolitic tuff, showing faster flow along the microfractured cooling joint surface (t = 26 minutes, reference marks at 10 mm intervals).

The significance of surface zone fast flow was quantitatively evaluated through measuring trends in cumulative water uptake in another sample of the welded tuff, through its fracture coating and then into its matrix. In homogeneous porous media, the short term volumetric water uptake rate per unit area follows diffusion-like behavior. Thus the cumulative imbibition (I) of water is linear with respect to the square-root of time, with the proportionality factor referred to as the sorptivity, S [Philip, 1957]. When such an experiment is done on a coating-matrix composite sample with the surface coating placed in contact with a free water reservoir, and imbibition into the low permeability matrix occurring via the coating, sorptivities in both layers can be deduced [Thoma et al., 1992]. Square-root of time plots for water entry through the Topopah Spring tuff fracture coating, then into the welded tuff matrix reveal that the sorptivity of the fracture coating is 5.5 times greater than that of the underlying matrix (Fig. 5). Since permeabilities are very well correlated with sorptivities raised to the fourth power [Kao and Hunt, 1996], the permeability of the Topopah Spring Tuff fracture coating is about 900 times greater than that of the matrix rock. Thus, gravity driven flow within this fracture coating can proceed with about 900 times greater velocities than in the immediately underlying matrix rock. Similar results were obtained for sorptivity measurements on the rhyolite (data not shown). Such extremely high contrasts in permeabilities are expected to exert strong influences on water infiltration during episodic rainfall events since much of the water percolates along fractures.

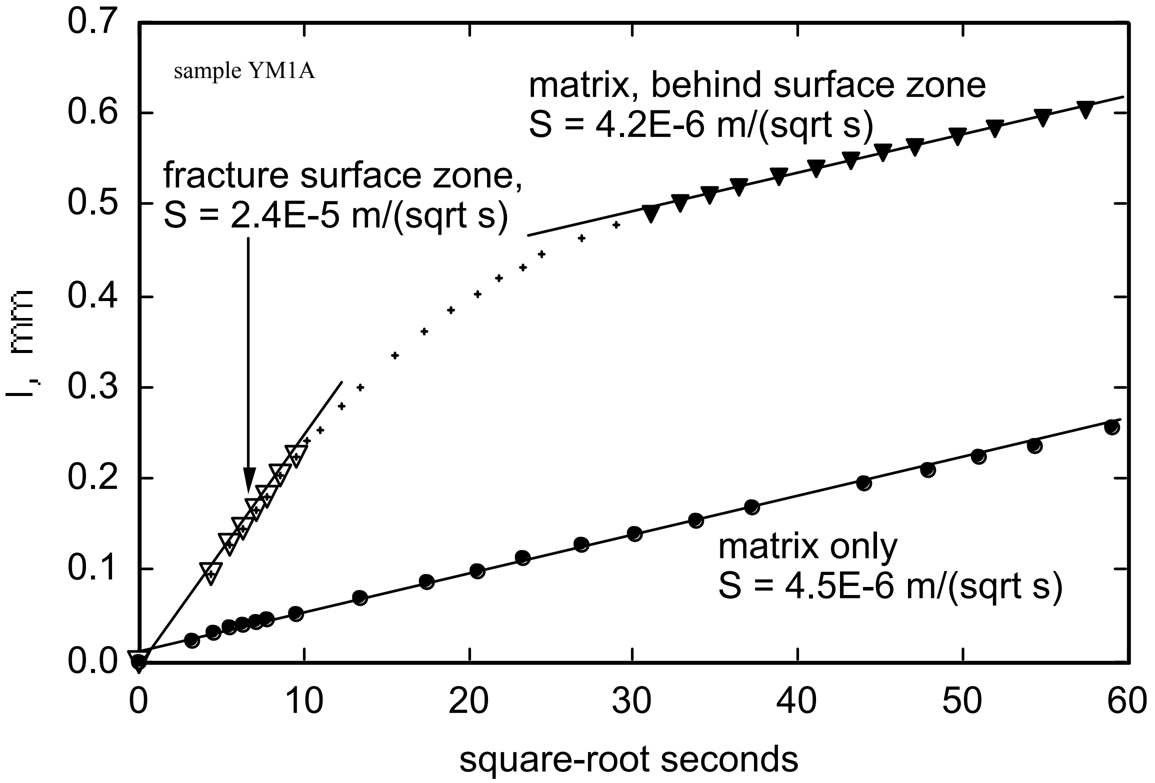

Figure 5. One-dimensional sorptivity experiments into a Topopah Spring Tuff. The upper curve is for imbibition through fracture surface coating, into the matrix. The lower curve is for imbibition directly into the matrix. Note that the upper curve can be analyzed in two parts, to reveal separate sorptivities (S) for the fracture coating and the matrix.

Conclusions

These results show that rock fracture surfaces and fracture surface zones can serve as fast flow pathways along essentially unsaturated fractures. Thus, explanations of unsaturated flow in fractured rock based upon conceptual models which consider only aperture distributions and average rock matrix properties are generally incomplete. During transient infiltration events, the low sorptivity of partially saturated, very low permeability rock can sustain near-zero matric potentials along fracture surfaces associated with preferential flow paths. The roughness of natural fracture surfaces permits film flow under such near-zero matric potentials. Alterations to fracture surface zones of very low permeability rock are most likely to be permeability-enhancing, thereby promoting flow along the fracture plane. The "opposite" case of low permeability fracture coatings enveloping higher permeability bulk rock also sustains fracture flow by impeding imbibition into the matrix. Thus, coatings will generally promote flow along fractures, regardless of whether or not they are higher or lower in permeability that the bulk rock matrix. For all of these reasons, film flow and surface zone flow can be especially important in understanding flow through unsaturated, fractured, low permeability rock. Although this study has identified two mechanisms contributing to fast unsaturated flow, it remains very important to quantify how fluxes are distributed with respect to flow velocities. Information on the proportion of total flow engaged in slow flow through bulk rock versus fast flow in fractures is required since this distribution determines the overall mass contribution of each process. Flux distributions need to be determined at the appropriate field-scale since the heterogeneous distributions of hydraulic properties along relevant flow paths need to be accounted for.

Acknowledgments

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