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Evaluating conceptual models of flow in unsaturated, fractured porous media

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ABSTRACT

Equivalent Continuum representations of fractured systems are generally presumed valid for fluxes significantly less than some “critical specific flux.” The present study examines this criterion by comparing experimental tests with model predictions. As specific flux was varied in laboratory tests, three flow regimes were identified: 1) fracture dominated flow, in which flow occurs as a continuous phase in the fracture, 2) transitional flow, in which flow occurs in discrete, disconnected drops in the fracture, and 3) matrix dominated flow. Calculated values of the critical specific flux correctly predicted the observed lower limit of fracture dominated flow, and both Equivalent Continuum and Discrete Fracture Models provided reasonable matches with observations for matrix dominated flow regimes; however, the transitional flow regime was not adequately described by any of the models tested. Previous studies have assumed unrealistic boundary conditions to maintain non-equilibrium fracture flow conditions, but the present study suggests that fast pathways can develop at much lower fluxes than previous believed.

INTRODUCTION

Equivalent Continuum Models (ECMs) are frequently employed for field-scale simulations involving large numbers of gridblocks because they are computationally efficient and require relatively few parameters. Alternatively, Discrete Fracture Models (DFMs) can be used to describe flow in smaller, more detailed problems with knowledge of the spatial distribution of the flow domains and where computational efficiency may be less of a concern. For field scale problems this is rarely the case, and ECM simulations are common. ECMs are generally held to be valid for fluxes “sufficiently” below a specific critical flux [Nitao et al., 1993]; however, the transition between the two regimes is poorly understood.

The objective of this study was to examine the transition from fracture to matrix dominated flow conditions, and quantify the lower bounds of fracture dominated flow. To accomplish this, a series of laboratory tests were conducted in which a specified mass flux was applied to the top boundary of a single fracture, bounded by well-characterized matrix blocks. The arrival time of the wetting front at several locations along the length of the fracture was compared with the analytical solutions of Nitao and Buscheck [1991], and numerical simulations generated using the EOS9 (Richards Equation) module of TOUGH2 [Pruess, 1987, 1991; Pruess et al., 1999].

LABORATORY EXPERIMENTS

In our experiments, a constant flux boundary condition was applied to a simple fractured porous media system consisting of two blocks of limestone, mounted into sealed frame, and separated by a uniform gap. A series of constant flux tests were conducted by supplying a controlled flux of water into the top of the fracture and observing of the dynamics of the flow in the fracture/matrix system. The following sections describe the experimental setup and materials properties in detail.

Experimental Apparatus

The experimental system consisted of a sealed frame in which the blocks of limestone that represented the matrix of our system could be securely fixed. The blocks of limestone measured 0.065m long, 0.05m wide and 0.61m high. Small shims were inserted on the corners of the blocks to form a fracture with uniform aperture of $7.62\text{X}10^{-4}$m. The frame was sealed to minimize any potential evaporative losses from the system.

Water was supplied to the top of the fracture by a syringe pump. A segment of fiberglass wick material was placed over the full width of the fracture and the water applied into the wick via a hypodermic needle. This was to reduce the potential for preferential flow from the needle tip and ensure a uniform top boundary condition. Water exiting the bottom of the fracture was conveyed to a collection bottle using another section of fiberglass wick material. The mass of water applied into and exiting the experiment was measured using both volumetric and gravimetric methods to carefully track the mass balance of the system.

A series of optical sensors [Wood et al., 2002] were used to measure the presence of water at specific locations along the fracture (at 0.05, 0.17, 0.29, 0.41, and 0.53 m from the top boundary), thereby allowing for direct measurement of the wetting front arrival time with depth and the velocity of the wetting front in the fracture. The optical sensors were polled at a rate of 100 Hz, to ensure accurate measurement of the water arrival at the various locations in the fracture. Figure 1 is a schematic of the experimental setup.

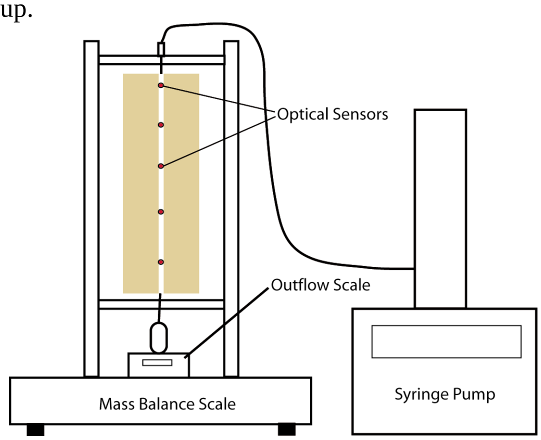

Figure 1. Experimental system used for the fracture flow experiments.

Material Properties

Matrix properties were determined using standard methods and testing in a UFA® ultra-centrifuge, and the saturation dependent properties described by the model of vanGenuchten [1980]. Repeated testing established the matrix properties with a high degree of precision, and demonstrated the blocks to be surprisingly homogeneous in character. It is standard practice to use unsaturated properties based on drainage curves, and this convention was followed by the present study to allow comparison with the results of other researchers. The numerical simulations presented below therefore neglect the effects of hysterisis.

Fracture permeability was estimated from the aperture using the parallel-plate solution to the Navier-Stokes equations. In order to minimize error when using the parallel-plate model to calculate fracture permeability, the brick faces were carefully machined to ensure a high degree of uniformity. Values of vanGenuchten α for the fractures were estimated from capillary theory assuming a contact angle of 0°, and the average half-aperture as the radius of curvature. The measured or estimated material properties were used to develop parameter sets for the numerical simulations using standard methods as discussed below.

ANALYTICAL MODEL

Nitao and Buscheck [1991] presented an analytical model describing the infiltration of water into an unsaturated, fractured porous medium. Asymptotic solutions for the position of the wetting front were provided for three time periods: early time ($t \ll t_b$, where t_b is the *matrix-fracture interaction response time*), before matrix imibition significantly affects fracture flow; late time ($t/t_a \gg 1$, where t_a is the *local matrix fill-up time*), after the matrix becomes nearly saturated with a quasi steady-state moisture content profile; and intermediate time ($t_b \ll t \ll t_a$), when the matrix imibition retards fracture flow and the velocity of the fracture wetting front decreases with a $t^{-1/2}$ dependence. Using these criteria, we calculated t_b and t_a for our experiment to be 4.13 and 1,897 seconds, respectively.

The expression for the position of the wetting front as a function of time used in the present study was [Nitao and Buscheck, 1991]:

$$h(t) = \tilde{q}_o \frac{t_b}{\pi} \left[e^{\pi t / t_b}\, erfc\left(\pi t / t_b\right)^{1/2} - 1 + 2\left(t/t_b\right)^{1/2} \right] \quad [1]$$

where $\tilde{q}_o$ is the velocity of the wetting front [m/sec] at the fracture inlet, defined as:

$$\tilde{q}_o(t) = q_o(t) / \phi_f \left(S_f^o - S_f^i\right) \quad [2]$$

For our analysis it can be expressed as:

$$\tilde{q}_o(t) = r_i / 2 b w \rho \phi_f \quad [3]$$

where r_i is the mass flux [kg/sec], b is the fracture aperture [m], w is the fracture width [m], ρ is the water density [kg/m^3], and ϕ_f is the fracture porosity.

The *specific critical flux*, q_f* (Nitao et al., 1993) is defined as:

$$q_f^* = \varphi_m \left(S_s - S_i\right) D_m \quad [4]$$

where ϕ_m is the matrix porosity, S_s is the maximum matrix saturation, S_i is the initial matrix saturation, and D_m is the matrix diffusivity. This is a convenient expression, as a flux value for matrix-dominated flow can be estimated from matrix properties alone. For our system, we define a *critical mass flux* rate, r_i*, by multiplying this expression by the width of the fracture and water density, so that:

$$r_i^* = \varphi_m w \rho \left(S_s - S_i\right) D_m \quad [5]$$

Using equation [5], the critical mass flux for our experiment is 5.18X10^{-5} kg/sec.

NUMERICAL MODELS

Equivalent Continuum Models

An equivalent single continuum property set for the ECM simulations was developed using methods of arithmetic averaging in the vertical direction (parallel to flow). The large fraction of the total area occupied by matrix blocks dominated the resulting property sets, which is expected given the assumption of fracture/matrix thermodynamic equilibrium inherent in the ECM conceptual model. Measured values of the vanGenuchten α and m parameters for the matrix were used without adjustment. Both isotropic and anisotropic property sets were developed for the ECM simulations; selected parameter values are given in Table 1.

Table 1. Selected properties used for the numerical simulations.

	Iso-ECM	Aniso-ECM	DFM
k_m [m^2]	$1.48\text{X}10^{-15}$	(h) $1.48\text{X}10^{-15}$ (v) $5.61\text{X}10^{-10}$	$1.48\text{X}10^{-15}$
k_f [m^2]	-	-	$4.84\text{X}10^{-8}$
α_m [Pa^{-1}]	$4.1\text{X}10^{-5}$	$4.1\text{X}10^{-5}$	$4.1\text{X}10^{-5}$
α_f [Pa^{-1}]	-	-	$5.0\text{X}10^{-3}$
m_m [-]	0.133	0.133	0.133
m_f [-]	-	-	0.800

Discrete Fracture Models

For the DFM simulations, elements were assigned parameter values strictly representative of either the fracture or matrix domains. Experimentally measured parameter values were used without modification for matrix properties. Fractures were included explicitly in the numerical grid as elements with the aperture assigned as the measured aperture divided by the fracture porosity, $2b/\phi_f$ [Nitao and Buscheck, 1991]. Fracture elements were assigned a porosity of 0.98, and values of fracture permeability and α, estimated as outlined above.

No accepted methodology exists for making *a priori* estimates of the fracture vanGenuchten m parameter, although measured values for fractures in limestone of approximately 0.8 have been reported in the literature [Reitsma and Kueper, 1994]. Therefore, a value of 0.8 was used with sensitivity studies conducted to determine the influence of this parameter on simulation results. Selected parameters used in the DFM simulations are shown in Table 1.

RESULTS

Five laboratory experiments have been conducted to date, starting with a mass flux rate chosen corresponding to the calculated critical mass flux rate ($5.18\text{X}10^{-5}$ kg/sec). Flux rates were then adjusted within the limits of the pump, from $5.18\text{X}10^{-4}$ to $5.18\text{X}10^{-8}$ kg/sec. Three flow regimes were qualitatively defined from the experimental observations: 1) fracture dominated flow, in which flow occurs as a continuous phase in the fracture, 2) transitional flow, in which flow occurs in discrete, disconnected drops in the fracture, and 3) matrix dominated flow. The bounds on these periods are qualitative, and further experiments will be required to quantify the limits of each regime; however, some interesting observations can be made based on the observations to date. The boundary between regimes 1 and 2 generally coincides with the value of specific critical flux [Nitao, et al., 1993]. The analytical and numerical solutions for the arrival time of the wetting front generally bound the experimental results in the fracture dominated flow regime, with the analytical results providing an earlier arrival and the numerical simulations providing a later arrival. Figure 2 shows the arrival time of the wetting front in the fracture at 0.41m.

In the transitional flow regime, water moved primarily through the fracture, but as a discontinuous phase. Individual droplets of water moved at a velocity intermediate between those observed in the purely fracture or matrix dominated flow regimes. Flow in the transitional regime may compare qualitatively with that observed by previous investigators in acrylic pipe [Germann, 1987; Germann et al., 1997] or, under certain circumstances, at the outflow of a laboratory experiment in porous media flow [Pra•ák et al., 1992]. Because of the discontinuous nature of the wetting phase, it was difficult to quantitatively define a “wetting front” for the transitional flow regime; however, fracture flow was observed to rapidly transit significant distances in this mode.

DISCUSSION

Analytical and numerical simulations of flow in single fracture within a porous matrix provide bounds on experimental observations. Numerical simulations of system behavior incorporate unrealistically high interaction between fracture and matrix continua, in qualitative agreement with the work of other investigators [e.g., Liu et al., 1998]. By contrast, the analytical solution of Nitao and Buscheck [1991] appears to provide too little fracture matrix interaction (at small times or high flux rates).

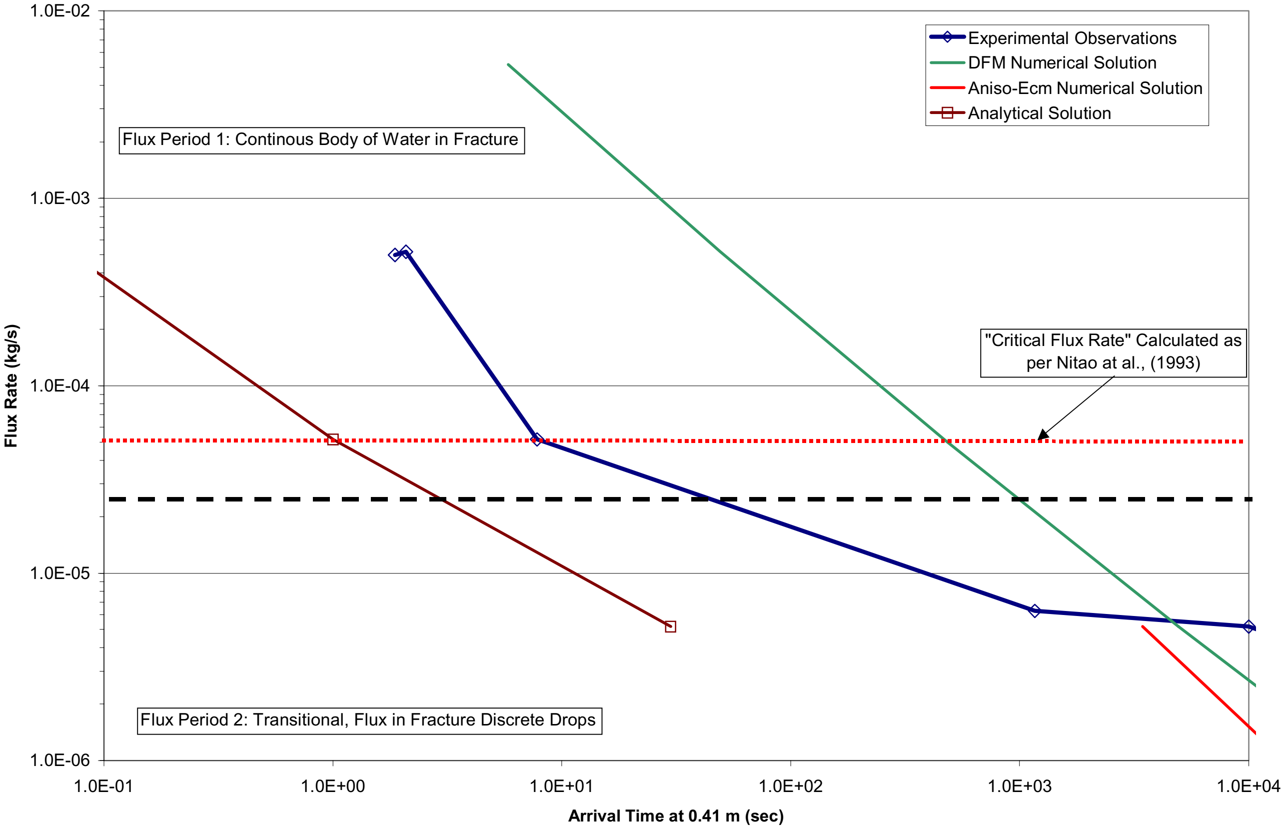

Figure 2. Plot of flux rate versus arrival time at 0.41m for the experimental, analytical, and numerical data.

The specific critical flux defines the transition between fracture-dominated flow and matrix-dominated flow, which has been shown to coincide with the applicability of the ECM [Nitao et al., 1993]. The specific critical flux for the system considered in the present work adequately identified the onset of the transitional flow regime between fracture and matrix dominated flow conditions; however, this transitional regime was observed to span several orders of magnitude change in specific flux. TOUGH2 simulations using ECM and Discrete Fracture Models (DFMs) indicate this discrepancy is attributable to competition between matrix imbibition and capillary suction in the fractures.

These observations are important because they demonstrate that relatively small fluxes can lead to unexpected behavior in a field situation. Scenarios in which fracture-dominated flow transited hundreds of meters of fractured, unsaturated porous media in a matter of days have generally been viewed as unrealistic, because large flux rates and/or persistent ponding at the upper boundary were necessary to maintain fracture dominated flow regimes. The present work is in agreement with other laboratory studies [e.g., Tokunaga and Wan, 1997], and field evidence [for a summary of field observations and review of alternative modeling strategies, see Pruess et al., 1999a] in suggesting that fast-flow pathways could develop in significantly less restrictive circumstances than previously believed. Clearly, understanding the conditions under which fast pathways develop in fractured media, and rigorously defining the limits of applicability of continuum representations of heterogeneous flow systems, necessitate further investigation of the transition between fracture and matrix dominated flow regimes.

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