Meso-scale estimates of unsaturated fractured rock fluid flow parameters

Todd C. Rasmussen & Daniel D. Evans
Department of Hydrology and Water Resources, University of Arizona, Tucson, USA

1 ABSTRACT

The calibration and validation of computer simulation models used to estimate fluid flow and solute transport through variably-saturated discrete fracture networks is a necessary step for performance assessment of subsurface geologic hazardous waste storage facilities. Methodologies for estimating parameters which govern fluid flow through fractured rock are presented. The methodologies include water infiltration and air flow tests on exposed rock surfaces, subsurface cross-borehole air flow and air-phase tracer tests along fractures, and water intake into fractures from inclined boreholes in unsaturated rock. The techniques demonstrate the feasibility of characterizing water flow through saturated fractures and air flow through unsaturated fractures. Techniques to estimate fluid flow parameters in variably saturated rock have not been demonstrated.

2 INTRODUCTION

Intermediate between laboratory-scale experiments and macro-scale characterization of large geologic features lies a class of meso-scale field experiments which are not only useful for performing confirmatory analysis of theoretical models, but also for providing parameters necessary for macro-scale computer models. While procedures for characterizing flow and transport through unsaturated soil materials have been examined extensively in the fields of soil physics, soil mechanics and others, some of the laboratory techniques are readily transferable to the assessment of rock matrix properties using rock cores while others require modifications to account for the normally lower porosities and permeabilities of consolidated geologic media and the difficulties of instrument emplacement and of adequate instrument/rock contact.

Laboratory-scale experiments, however, are inadequate for examining the water conducting and contaminant transport properties of natural fracture systems. These properties must be assessed in situ utilizing various testing procedures which have only recently been examined for unsaturated fractured rock, and then only for fluid flow and not contaminant transport. The methods to be described in this paper use either air or water injection procedures to characterize individual fractures and fracture connections. The methods have been field tested at volcanic tuff sites near Tucson, Arizona.
3 FORMULATION OF LIQUID AND GAS FLOW THROUGH NATURAL FrACTURES

The fluid mass flow rate, $v_m$ (in kg/m²s), for both liquids and gases can be expressed by (e.g., see Hunkat, 1946):

$$v_m = -k/\mu \text{ grad } P_a,$$

where $k$ = permeability, m²;
$\mu$ = dynamic viscosity, kg/m s;
grad = differential operator, 1/m;
$r$ = fluid density at ambient temperature and pressure, kg/m³; and
$P_a$ = fluid pressure at ambient temperature, Pa.

Equation (1) can also be written in a form which relates volumetric flow of an incompressible fluid to pressure head:

$$Q = -A K \text{ grad } h,$$

where $Q$ = volumetric flow, m³/s;
$A$ = cross-sectional area normal to the direction of flow, m²;
$K$ = hydraulic conductivity, equal to $k/\mu$ in m²/s where $g$ = gravitational constant, m/s²; and
$h$ = ambient pressure head, m.

Equation (2) is appropriate for laminar flow of water and for gas in response to a small pressure gradient. For individual fractures, the cross-sectional area can be written as the product of the mean fracture aperture, $a$ (m), and the extent of the fracture normal to the direction of flow, $w$ (m), (i.e., $A = a w$). Flow per unit width normal to the direction of flow, $q$ (m³/m²) is:

$$q = Q / w,$$

The use of Equation (3) requires the estimation of the mean fracture aperture and the fracture permeability, both of which are difficult to measure. The estimation problem is simplified by defining a new parameter as the product of aperture and permeability, either as a fracture permeability, $K_f$ (m²) or fracture transmissivity, $T_f$ (m²/s):

$$K_f = e K,$$

and

$$T_f = e K/\mu w g,$$

Either parameter can be used to relate a driving force to volumetric flow. Both parameters will incorporate the effects of tortuosity, variable aperture and other sources of flow impedance. Also, they will be a constant for conditions of air flow through a drained fracture and water flow through a saturated fracture.

To aid in the interpretation of experimental results, an equivalent parallel plate aperture expression can be used as an index of fracture permeability. While the assumption of parallel plate flow in natural fractures is weak, it does allow the fracture permeability and transmissivity to be related to an apparent hydraulic aperture, $a_h$ (m²), using:

$$k = e a_h^2/12,$$

Air flow through a natural fracture under controlled laboratory conditions (Schraufnagl and Evans, 1986) have been shown to be useful for calculating an equivalent hydraulic aperture. These apertures were compared to observed average apertures for a fractured granite rock (Figure 1).

4 FIELD TESTS OF WATER AND AIR INTAKES INTO SURFACE-EXPOSED FRACtURES

The water source for a thick unsaturated zone is often from precipitation and infiltration at the land surface. For a rock with only a thin stock cover and saturated, water intake is likely to be fracture controlled. A densely-welded tuff near Tucson, Arizona, with a horizontal surface and exposed vertical fractures was selected to evaluate a fractured rock infiltrimeter which was designed and constructed for measuring the vertical infiltration rate versus time for selected fracture segments (Kilbury et al., 1986).

A plot of the cumulative intake amount, derived fluid velocity, and depth to wetting front is presented as Figure 2. The curve resembles intake rates in unconsolidated media, with an initially high fluid velocity followed by decline to an asymptotic rate. Calculated fracture permeabilities and apparent hydraulic apertures for measured fracture segments are plotted in Figure 3. The values range from 1 to 30 μm and appear as log-normal distributions for different aperture size ranges.

To estimate mean-scale intake rates, the total length of fractures for an exposed surface area of 1.4 hectares was determined. The probability distributions shown in Figure 2 were applied to the total fracture length to obtain an average intake rate for the area (Kilbury, 1984). A stochastic rainfall model for the site was coupled to the deterministic runoff/infiltration model using the experimental data to calculate mean annual intake rates over a ten-year period. Only 2 mm of the 44 cm average annual precipitation was estimated to infiltrate.

The fractured rock infiltrimeter design allowed the measurement of fracture air permeability for the same fracture segments as were used for water intake measurements. Air permeabilities were measured two days prior to the water measurement for ten fracture segments. The results, plotted in Figure 4, are similar for the two fluids, indicating little change in the fluid conducting properties of the fracture segments during the measurement interval. The effect of fracture water content on flow rates is shown in Figure 5. Curve A is a plot of air intake into an initially dry fracture segment; Curve B is a plot of water intake into the same initially dry fracture segment; and Curve C is a plot of air intake after the fracture segment had been wetted. It is interesting to note the rapid increase in air-phase permeability over time following the wetting phase.

5 CROSS-HOLE AIR INJECTION TESTS

A pneumatic cross-hole method was assessed to determine the fluid conducting properties of fractures below the land surface (Trafts, 1984). Pairs of horizontal 5-cm diameter boreholes were drilled into tunnel walls in welded tuff. Pressurized borehole curves, the location and orientation of fractures for each borehole were logged. Suspected fracture connections between boreholes were identified and then tested by sinking off the fractures in each borehole and monitoring for a pressure response due to an air-injection test.
Figure 1. Comparison of average fracture aperture and apparent fracture aperture.

Figure 2. Cumulative water intake (A), inferred fluid velocity (B), and inferred depth to wetting front (C) for a representative intake curve using a fractured rock infiltrometer.

Figure 3. Log-log probability plot of apparent hydraulic aperture and fracture permeability computed from water intake rates using a fractured rock infiltrometer.

Figure 4. Plot of apparent hydraulic aperture and fracture permeability computed using air (open circles) and water (closed circles) intake rates for the same fracture segments.

Figure 5. Sequence of experiments, starting with air intake experiment for an initially dry fracture (A), followed by a water intake experiment (B), and terminated with a repeated air intake experiment (C) on the same fracture segment.

6 Fracture Connectivity Between Inclined Boreholes

Nine boreholes inclined at an angle of 45° were installed along three parallel lines (Figure 6) in a slightly-welded tuff near the densely-welded tuff site. Oriented cores from the 10-cm diameter bore-
Holes were used to locate fractures which might provide conduits for fluid flow between the boreholes. Cross-hole air injection tests were not performed because of insignificant pressure responses in observed boreholes. Instead, a cross-hole air-phase tracer test (Brekke, 1986) was used to determine fracture connectivity between boreholes. The test consists of injecting helium gas (which is relatively inactive in water, chemically inert, inexpensive and detectable to levels of 1 \(10^{-6}\) cm/s) into a packed-off interval of one borehole and monitoring the gas at locations of suspected fracture intersections. Figure 7 presents a diagram showing the test configuration. Figure 8 presents helium concentrations in the observation borehole at three separate lines. The breakthrough of helium originates in a fracture zone consistent with the orientation of a fracture trace in the injection borehole.

7 WATER INTAKE RATES IN INCLINED BOREHOLES

A downhole heat-pulse flowmeter (Meseer, 1986) is being used to estimate fracture intake rates from the inclined boreholes when filled with water. Each borehole is sequentially filled with water and a constant water level is maintained during the course of an experiment. The regional water table is sufficiently deep to not affect the experiment. Flow measurements are started after steady state flow has developed. The downhole flowmeter is located at various depths and the downhole flow rate is measured at each depth. The depths are selected to provide intake rates into individual fractures or groups of fractures. Intake is calculated as the difference between borehole water flow rates at two depth flows measured within the range of 0.005 to 0.400 l/min.

Results for Borehole Y-3 are presented as Figure 9. Indicated in Figure 9 are the borehole intake rates in liters per minute for selected intervals. A difference of 0.005 l/min is significant. That fracture flow dominates matrix flow for saturated conditions can be supported by measurements of water content using a neutron probe which show a high degree of correlation with fracture density and water intake rates.
The method gives a good characterization of saturated flow properties of a fractured rock with depth and degree of fracturing.

3 DISCUSSION

Results from the methods presented in this paper support the conclusion that fractures provide a conduit for water flow in saturated volcanic tuffs and to air flow in unsaturated tuffs. It is also demonstrated that the fracture permeability is constant for both air and water. A distribution of fracture permeabilities is used to estimate regional intake rates to surface-exposed rock fractures. In addition, fracture connectivity at depth is demonstrated using cross-hole air injection tests, helium tracer tests and borehole intake tests. Procedures for estimating the effect of variably-saturated fractures on water flow through the rock matrix and fractures has not been demonstrated.

REFERENCES


