FRACTURE SYSTEM CHARACTERIZATION FOR UNSATURATED ROCK

D.D. Evans and T.C. Rasmussen
University of Arizona, Tucson, AZ 85721

T.J. Nicholson
Nuclear Regulatory Commission, Washington, D.C. 20555

ABSTRACT

Techniques for estimating fluid flow through fractured volcanic tuffs are presented. The techniques include water infiltration and air flow tests on exposed rock surfaces, cross-hole borehole air flow tests along fracture planes, and fluid losses from a slanted borehole in the unsaturated zone. The methods demonstrate that methodologies are available for characterizing fracture flow through saturated fractures. The ability to characterize flow and solute transport through partially-saturated fracture networks has not been demonstrated.

INTRODUCTION

The U.S. Nuclear Regulatory Commission has published final regulations related to the disposal of high-level radioactive wastes in geologic repositories (46 FR 13971 and 48 FR 28194). While these regulations were first limited to geologic repositories in the saturated zone, subsequent interest by the U.S. Geological Survey and the U.S. Department of Energy in the possibility of locating a repository in the unsaturated zone resulted in modifications which included unsaturated geologic media (50 FR 29641).

Because ground-water migration is considered to be the most important pathway for radionuclide transport away from a repository, one of the important issues which must be addressed during the evaluation of the suitability of any repository site is the effectiveness of the site in isolating radioactive waste from the accessible environment for the necessary period of time. While many positive aspects and concerns associated with disposal in the unsaturated zone have been identified (1,2,3,4), water flow and radionuclide transport processes in unsaturated media are significantly different from those for saturated media and require special characterization procedures.

The potential repository site under consideration in the United States with unsaturated conditions is Yucca Mountain at the Nevada Test Site. The unsaturated zone at Yucca Mountain extends to several hundred meters and has several volcanic tuff strata with varying degrees of welding and fracturing. Water flow, and hence the transport of solutes, is through the rock matrix as well as through the existing fracture system. The dominance of one flow path over the other depends upon the relative conductivities of the rock matrix and the fracture system at the existing rock water potential. Even at constant water percolation rates, the rock water potential can vary in different tuff members as a function of matrix properties. As a result, the dominant flow and transport process can vary with depth.

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. Others require modifications to account for the normally lower porosities and conductivities of consolidated geologic media and the difficulties of instrument emplacement and of adequate instrument/rock contact. In general, properties of a rock mass can be estimated from rock core data.

It is important to note, however, that the water conducting and contaminant transport properties of a natural fracture system must be assessed _in situ_ utilizing various testing procedures. Such procedures for unsaturated fractured rock have only recently been examined and they deal with fluid flow only and not contaminant transport. The methods to be described use either gas or water injection procedures to characterize individual fractures or fracture connections. The methods have been field tested at volcanic tuff sites near Tucson, Arizona.

WATER INTAKE 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 soil cover and with an extremely low matrix permeability, water intake is likely to be fracture controlled. To evaluate methods for estimating intake rate for a fractured surface, a site was selected near Patagonia, Arizona, where densely welded tuff was exposed on a nearly horizontal surface (5). The fracture system had a vertical fracture set and these fractures could be clearly observed at the land surface. An infiltrometer was designed and constructed for measuring the vertical infiltration rate versus time for selected 41 cm long segments of surface exposed fractures.

The results can be expressed as a volumetric flux at the surface or as an apparent fracture conductivity or permeability. For some purposes, an equivalent parallel plate aperture expression can be used as an index of fracture permeability to aid in the interpretation of results. It is important to recognize that an equivalent aperture is proportional to the square root of the fracture permeability and the cube root of volumetric flux.

A representative infiltration curve for a fracture segment is shown in Fig. 1. The curve is typical of that for unconsolidated media, initially relatively high and reducing with time to a nearly constant value. The calculated equivalent apertures for all fracture segments measured are plotted in Fig. 2. The values range from 1 to 30 μm and appear as log-normal distributions for different aperture size ranges.

To estimate intake rates for an exposed surface area of 1.4 hectares, the total length of fractures for the area was determined and the probability distributions shown in Fig. 2 were applied to the total length to obtain an average intake rate for the entire area (6). A stochastic rainfall model for the site was coupled to the deterministic runoff/infiltration model (using the experimental data) to calculate cumulative water intake for a ten-year period. Of the 442 mm average annual precipitation, only an estimated 2 mm infiltrated and would be available for evapotranspiration or deep percolation.

The water infiltration apparatus was modified to measure fracture air permeability for selected fracture segments. Air permeabilities were measured just prior to the water measurement for ten fracture segments and the results are plotted in Fig. 3. The results for the two fluids are similar, indicating laminar flow for both fluids and little change in the fluid conducting properties of the fracture segments during the measurement interval. The consistently lower value for water compared to air may be the result of a rearrangement of unconsolidated fracture-filling particles during the application of water.

Air flow through a natural fracture under controlled laboratory conditions (7) have been shown to be useful for interpreting air flow field tests. Ref. 7 presents data to show the transition from laminar flow to turbulent flow with increase in pressure gradient and a single equation to represent the full pressure range. Also, calculated equivalent hydraulic apertures were compared to measured average apertures.

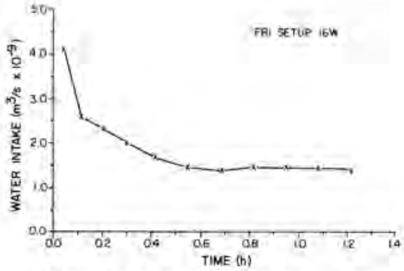

Fig. 1 Water intake rate versus time for a representative FRI water experiment.

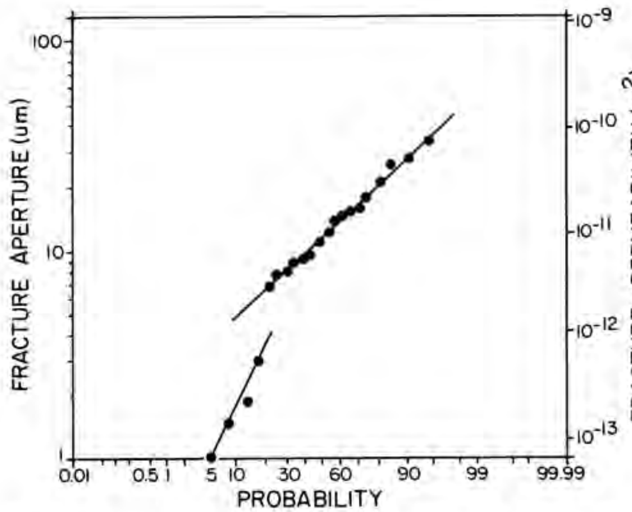

Fig. 2 Log-probability plot of fracture apertures and fracture permeability computed for the FRI water method.

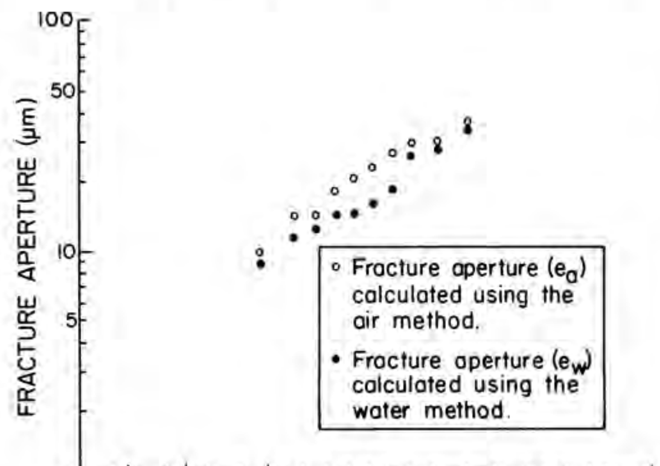

Fig. 3 Log-probability plot of fracture apertures computed using the air and water methods on the same fractures.

AIR INJECTION PARALLEL BOREHOLE TESTS

To determine the fluid conducting properties of fractures below the land surface, a pneumatic cross-hole method was assessed (8). Pairs of nearly horizontal, 5-cm diameter boreholes were diamond core drilled into the wall of a tunnel near Superior, Arizona, penetrating densely welded tuff. Each parallel pair of boreholes was separated by 0.89 m and extended 15 m into the rock. The cores were logged to determine the location and orientation of fractures for each borehole.

Fracture connections between boreholes were estimated and then tested by packing off suspected connecting fracture/borehole intersections and performing air injection/pressure response tests between the two boreholes. Confirmed connecting fractures were tested by injecting nitrogen gas at different pressures into a packed off section of one borehole and measuring the pressure changes in the observation borehole. The injection and observation boreholes were then reversed and the measurements repeated. Both linear and nonlinear flow equations were developed for radial and elliptical flow conditions. Radial flow occurs when the axis of the injection hole is perpendicular to the fracture plane, while elliptical flow occurs when the fracture plane is other than perpendicular. The effects on flow rates of hidden fracture intersections near the injection borehole were also examined.

Calculated equivalent hydraulic apertures ranged from 9.0 to 200 μm for the ten fractures examined. The effect of partial water blockage was observed for two flow tests following a rainfall event. Pneumatic tests appear to give reasonable estimates of fracture air permeabilities and equivalent hydraulic apertures. The studies show that accurate fracture orientation data of each fracture tested are necessary to analyze the experimental data.

WATER INTAKE FROM SLANTED BOREHOLES

Water intake rates were measured for fractures intersecting 10-cm diameter boreholes diamond core drilled into slightly welded tuff at a 45 degree angle using a downhole flowmeter (9) The location and orientation of the intersected fractures for three boreholes in the same vertical plane are shown in Fig. 4. The fractures were initially unsaturated and the water table was sufficiently deep to not influence water from the boreholes during the time of measurements. Each borehole was sequentially filled with water and a constant water level was maintained during the course of a measurement. Flow measurements were started after steady state flow had developed.

The flowmeter was located at various depths and the downhole flow rate was measured at each depth. The depths were selected to yield outflow into individual or groups of fractures by the difference in borehole water flux at two depths. Results for the three wells are included in Fig. 4. The numbers associated with the arrows are the borehole flow rates in liters per minute at that depth. The difference between any two adjacent numbers is the rate of water loss in the section of borehole between the two arrows. A difference of 0.005 l/min is significant. The method gives a good characterization of saturated flow properties of a fractured rock with depth and degree of fracturing.

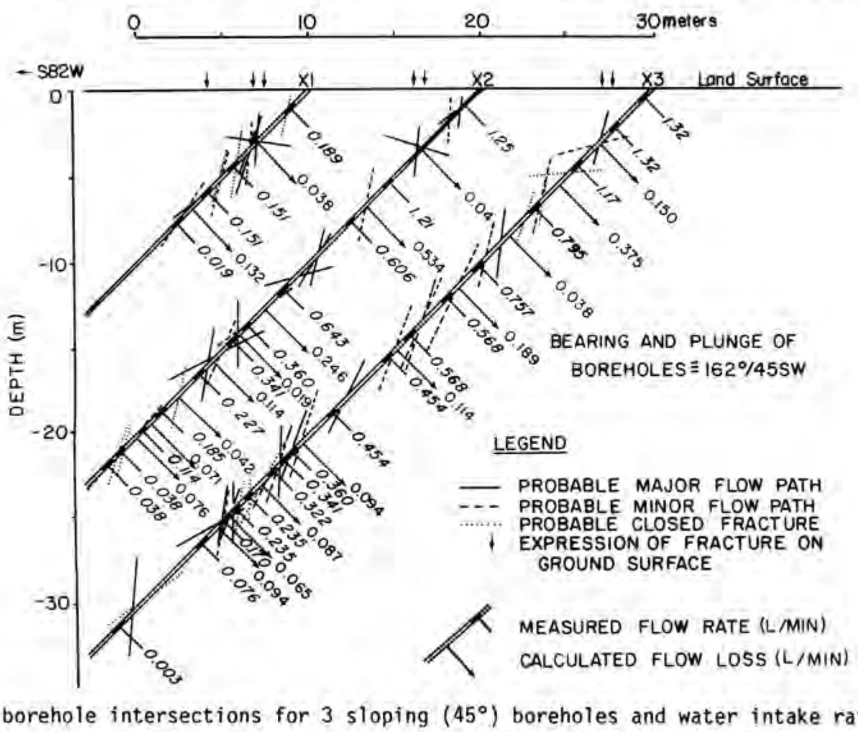

Fig. 4 Fracture borehole intersections for 3 sloping (45°) boreholes and water intake rates for different segments of each borehole when the water level was maintained at the surface.

DISCUSSION

The three methods discussed above appear appropriate for the partial characterization of the hydraulic properties of an unsaturated rock mass as related to the isolation of radionuclides that may be released from a repository. Results from all of the methods, using air or water, normally would apply only to water saturated conditions or to gas flow, and mainly to individual fractures. For further site characterization of a fracture system, fracture connections between boreholes are needed. It appears that sufficient data for describing frequency distributions of fracture parameters can be collected for saturated conditions to computer generate realistic fracture systems for flow and radionuclide transport simulation experiments.

For unsaturated conditions, a critical measurement is the fracture hydraulic conductivity as a function of rock water potential. Procedures for this measurement have not been developed. Spatial variations in natural fracture surfaces and apertures result in a characteristic drainage curve with a decrease in water potential and a concomitant decrease in hydraulic conductivity. Both functions would show hysteresis which complicates their determination.

In addition to the interest in unsaturated fractured rock studies for high-level radioactive waste isolation, interest is developing in site characterization and monitoring such geologic settings related to occurrence and disposal of other types of contaminants. Numerous solid waste disposal sites exist in saturated and unsaturated fractured rock settings and must also be monitored (Resource Conservation and Recovery Act, Subtitle D).

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