Special Problems in Sampling Fractured Consolidated Media

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INTRODUCTION

The flow of water and the resulting transport of contaminants through unsaturated fractured media is a serious concern at many existing and potential waste disposal sites. Techniques for characterizing fractured media in the unsaturated zone are less established than techniques applied in saturated fractured rock or in unconsolidated media. This is due, in part, to difficulties associated with developing predictive models and devising monitoring methods suitable for characterizing contaminant migration in such media. The unique features of unsaturated fractured rock, such as the paucity of field data and the inability to identify networks of interconnected fractures over large distances, pose special problems when sampling for physical and chemical properties.

Fractures tend to increase the heterogeneity of hydraulic parameters relative to an unfractured medium, thus increasing the spatial variance of contaminant distributions. For infiltration into a dry soil with uniform hydraulic properties, a uniform contaminant distribution with depth is normally expected. As a contaminant infiltrates into a fractured rock, however, the contaminant often advances as fingers through the fracture system, bypassing much of the matrix, as seen in Figure 28.1A (Haldeman et al., 1991). Water and entrained contaminants also move into the matrix from the fracture due to concentration gradients associated with Fickian diffusion, and total head gradients associated with gravitational and pressure gradients (Figure 28.1B). Thus, there may exist a contaminant gradient both within and away from fractures. This spatial and temporal complexity in unsaturated fractured media adds greatly to the design of sampling protocols and the interpretation of observed contaminant concentrations.
the fractures are air-filled, only an additional slight rise in gas permeability is observed as the matrix drains. Vapor transport of contaminants is governed by processes very similar to liquid transport, with the major difference being the substantially lower viscosity of gas as opposed to liquids. This viscosity contrast yields much greater vapor transport velocities, given similar total head gradients and saturations relative to the transport phase.

Containment sampling strategies in the consolidated and unconsolidated media are substantially different because of the significant differences in pore structure and pore continuity. Unconsolidated media transport properties are generally more time-dependent due to rapid changes in saturation and temperature near the surface. Flow fields in consolidated media are generally less time-dependent because they lie below unconsolidated media, thus reducing the influence of surface perturbations. While fractures in competent porous rock may respond to subsurface-imposed mechanical stresses and temperature perturbations (such as near a high-level nuclear waste repository), such changes are seldom encountered under natural conditions. In contrast, fractures in expanding and shrinking soils exhibit dynamic spatial and temporal behavior. Such soils often display cyclical fracture formation and filling with soil material on daily, seasonal, and annual intervals.

The material presented here is a summary of insights gained from over ten years of experimental field work by the University of Arizona at unsaturated field sites in fractured rock in Arizona. Characterization and model evaluation activities focusing on laboratory and field data at the Apache Leap Tuff Site, the Gringo Gulch Site, and the Santo Niño Mine Site have provided the opportunity to test alternate formulations for understanding the complex phenomena associated with unsaturated fractured rock and transport. It is hoped that the expertise developed and tested at these sites might be used at other sites to enhance the understanding of the complexity and the predictive capability for resolving the unique problems of flow and transport at each site.

DESCRIPTION OF APACHE LEAP TUFF SITE

The Apache Leap Tuff Site (ALTS) is located near Superior, Arizona, approximately 160 km north of Tucson, Arizona in the uppermost part of an approximately 20 million year old tuff formation. The formation varies from a slightly welded unit on top, through a moderately welded unit below, to a densely welded unit near the base of the formation. The base of the unit is composed of a nonwelded unit underlying a vitrophyre. The tuff covers an area of approximately 1000 km² and has a maximum depth of 600 m, with an average thickness of approximately 150 m. About one kilometer to the west of the Apache Leap Tuff Site is a 600-m escarpment, and immediately to the north there is a 200-m drop-off. The rest of the surface is dissected by ephemeral streams. The topography of the experimental area is nearly level compared to the surroundings.

Linear fracture traces are present, with some fractures containing a slight depression filled with unconsolidated material. These conditions provide an important water reservoir for water intake by the fractures. The annual average precipitation at the 1200-m elevation site is approximately 640 mm. Precipitation occurs in two seasons, from mid-July to late-September (characterized by high-intensity, short-duration thunderstorms during periods of high temperature and evapotranspiration demand), and from mid-November to late-March (characterized by longer duration

Figure 28.2. Contaminant transport may be (A) enhanced due to rapid transport through saturated fractures, or (B) reduced due to air-filled barriers associated with unsaturated fractures.
and lower intensity storms during cooler periods with much lower evapotranspiration demands.

To obtain parameters for the rock matrix and the fractures at the site, three sets (named X-, Y-, and Z-series) of three boreholes (named 1, 2, and 3) each were installed with each borehole at a 45° angle from the horizontal. A diamond bit drill was used for installing the boreholes. The drill was also used to cut a 6.35-cm diameter core. A specially designed scribing technique provided an orientation mark every 1.52 or 3.05 m along the borehole. Nearly 100% core orientation for all boreholes was obtained by using the scribe marks. Approximately 270 m of oriented core were obtained. The 10-cm diameter boreholes of each set are in a vertical plane and offset by 10 m. The sets are parallel and offset by 5 m. Sets X and Y dip to the west, while set Z dips to the east. The variable lengths, approximately 15, 30, and 45 m, provide fracture-borehole intersections for individual fractures at different depths below the surface.

Characterization data sets for the tuff matrix were obtained from the oriented cores using sections cut from the core at approximately three-meter increments. Three segments are removed from each section. The segments are labeled ‘large’ (5 cm long by 6-cm diameter), ‘medium’ (2.5 cm long by 2.5 cm diameter), and ‘small’ (1 cm long by 1 cm diameter) to differentiate between the three segments. The nine boreholes provide ready access for various in situ measurements, while the cores provide information on fracture spacing and orientation as well as samples for measuring matrix properties in the laboratory. To control water inputs (e.g., precipitation and outputs (e.g., evaporation) at the test area, the area was covered with plastic to a distance of 10 m in all directions beyond the boreholes, for a total area of 1500 m². Surface water is directed away from the site to prevent wetting of the region around the boreholes.

**NATURAL WATER AND AIR FLOW IN FRACTURED MEDIA**

The relationship between saturation and suction, called the moisture characteristic curve, in a fracture is a function of the distribution of fracture apertures and the nature of the interconnections between voids and contacts along the fracture walls. For parallel plates separated by a constant gap, or aperture, the moisture characteristic curve is a step function, with the critical suction at which the fracture changes between saturation and desaturation calculated using capillary theory:

\[
\psi_c = \frac{\gamma e \cos \alpha \tan \beta}{\gamma}
\]  

where 
\[
\psi_c = \text{critical suction head, m;}
\]
\[
\tau = \text{liquid surface tension, Pa.m;}
\]
\[
\gamma = \text{liquid specific weight, Pa.m}^{-1};\] and
\[
e = \text{fracture aperture, m.}
\]

Liquid flow along this idealized fracture, which by definition is non-existent when the fracture is drained, is calculated using the following expression:

\[
q = \frac{Q}{A} = T_r i
\]  

\[
T_r = \begin{cases} 
0 & \psi_c < \psi \\
\frac{(\tau^2 \gamma)}{(12 \mu)} & \psi_c > \psi 
\end{cases}
\]  

and

\[ q = \text{liquid flux per unit width of fracture normal to the direction of flow, m}^2\text{s}^{-1}; \]
\[ Q = \text{total liquid flow through fracture, m}^3\text{s}^{-1}; \]
\[ T_r = \text{fracture transmissivity, m}^2\text{s}^{-1}; \]
\[ i = \text{total head gradient along fracture, dimensionless; and} \]
\[ \mu = \text{liquid dynamic viscosity, Pa.s}. \]

Equations 2a and 2b may also be used to find the flow rate of a gas through a fracture if appropriate physical constants are inserted. In this case, the flow of gas is non-existent when the fracture is water-saturated. An additional feature of gas flow through porous media is the Klinkenberg slip-flow effect in which the gas tends to exhibit a higher flow rate than predicted due to nonzero velocities along the fracture walls. This effect only becomes significant in pores smaller than 1 μm, and generally does not affect gas flow in a fracture.

For geologic media that consist of significant nonfracture permeability, flow across the fracture, from one wall to the other, is also possible. In this case, the total head drop across the fracture from one wall to the other is zero if the fracture is saturated, and can increase to infinity for a drained fracture. This relationship can be formulated using the following expressions:

\[
q' = \frac{Q}{A} = C_r \Delta H
\]  

where

\[
C_r = \begin{cases} 
0 & \psi_c < \psi \\
\infty & \psi_c > \psi 
\end{cases}
\]  

and

\[ q' = \text{flow rate across fracture per unit area of fracture, m}^2\text{s}^{-1}; \]
\[ Q = \text{total flow across fracture, m}^3\text{s}^{-1}; \]
\[ A = \text{fracture area, m}^2; \]
\[ C_r = \text{fracture conductance, s}^{-1}; \] and
\[ \Delta H = \text{total head drop across fracture, m.} \]

For more realistic natural fractures in which the aperture is spatially variable, more complex relationships between suction, saturation, and fracture transmissivity are expected (Rasmussen, 1987; Vickers, 1990). Even with these more complex functions, however, the same general monotonic tendencies are expected (Myers, 1989). Experiments to identify these relationships and their trends are difficult to perform, however, and even slight changes in fracture normal and shear stresses may alter these relationships (Schrauf and Evans, 1986). These general relationships can
be related to the direction and magnitude of water migration if the tensorial form of Darcy’s law is written for unsaturated media:

$$ q = -K(\phi)i $$

(4)

where

- $q$ = vector of liquid flux, m s$^{-1}$;
- $K(\phi)$ = suction-dependent hydraulic conductivity tensor, m s$^{-1}$; and
- $i$ = total fluid head gradient vector, dimensionless.

Spatial variations in liquid suction, $\phi$, affect both the total head gradient vector, as well as the hydraulic conductivity tensor.

A simple approach for obtaining the hydraulic conductivity tensor is to decompose the fracture and matrix hydraulic conductivities ($K_f$ and $K_m$, respectively) into two, overlapping continua (Figure 28.4A), in which the effective permeability is the sum of the two permeabilities (see, e.g., Wang and Narasimhan, 1993):

$$ K_e = K_f + K_m $$

(5a)

where

$$ K_f = d_f T_f $$

and

$$ d_f = \text{fracture density, m}^{-1}; \text{ and} $$

$$ K_e = \text{effective hydraulic conductivity for fractured medium, m s}^{-1}. $$

Because this type of formulation assumes instantaneous equilibration of total head between the two media, essential features of the flow dynamics are overlooked. Such phenomena as capillary barriers (in which an unsaturated fracture impedes fluid flow) and rapid transient responses are, or should be, an important component of flow prediction and monitoring. This formulation also assumes that the flow direction is parallel to the plane of the fracture (Figure 28.3A).

Fractures may be open, partially filled, or completely filled with in-place weathered primary and secondary minerals, or with organic and inorganic materials that have been transported from other locations. These fracture fillings and wall coatings may greatly alter physical and chemical interactions of fluids and contaminants within the fracture as well as in the host rock surrounding the fracture. As such, the effective permeability may be more appropriately calculated using the harmonic average of the fracture and matrix permeabilities (see, e.g., Rasmussen et al., 1989):

$$ K_e^{-1} = d_f C_f^{-1} + K_m^{-1} $$

(5b)

where $K_e$ is the effective hydraulic conductivity of the fractured medium. This formulation is more appropriate for flow perpendicular to the plane of the fracture (Figure 28.3B).

Fracture flow is often a transient hydraulic response during and immediately following precipitation events. At the Apache Leap Tuff Site, water velocities in fractures due to the infiltration of rainfall were estimated using known rainfall and runoff rates, and by accounting for losses due to evaporation and infiltration into the rock matrix (Rasmussen and Evans, 1993).

This water budget approach yielded a mean water intake rate of from 2 to over 7 m hr$^{-1}$. Water velocities in the fracture estimated from this intake rates and observed fracture densities (0.77 m$^{-1}$) were found to range from 122 to 293 m hr$^{-1}$, indicating the possibility for very rapid movement to great depth within the subsurface. Water flow in fractures propagates downward, either until the water table is reached, the water is imbibed into the porous matrix surrounding the fracture, or the water is discharged to the surface from the fracture system at a lower elevation.
Inclined fractures can intercept water percolating downward within a rock matrix. It can be shown (Rasmussen et al., 1989) that for inclined fractures lying at an oblique angle, \( \alpha \), to the vertically percolating water, the effective hydraulic conductivity is an average of the arithmetic and harmonic averages calculated above:

\[
K_e = \frac{K_a \cos^2(\alpha)}{K_b + \sin^2(\alpha) / K_a}^{-1}
\]

(5c)

where \( K_a \) is the harmonic effective hydraulic conductivity calculated using Equation 5b and \( K_b \) is the arithmetic effective hydraulic conductivity calculated using Equation 5a. It is interesting to note that Equation 5c is the same result as would be obtained using a tensorial form, thus establishing the utility of Equation 4. Fracture flow in the vadose zone can also occur in zones where the rock hydraulic conductivity falls to a value less than the downward water percolation rate. In this circumstance, fracture flow will increase as the matrix permeability decreases.

Air and vapor movement is generally less affected by gravitational forces than water transport; being instead more sensitive to air pressure, gas density, and temperature gradients. In areas with topographic relief, differential surface-subsurface temperatures cause a gradient in air density that results in forced convection of air through the subsurface (see, e.g., Weeks, 1987; Kipp, 1987). Barometric pressure changes also cause subsurface air movements. Air flow is more pronounced in fractures than in the rock matrix for both pressure and density driving forces. The higher air permeability associated with drained fractures results in preferential air flow that can penetrate to great depths (Smith, 1989). Also, vapor transport is enhanced by the natural air flow through the subsurface, induced by both pressure- and density-driven driving forces.

The prediction of gas flow requires that Equation 4 be rewritten in terms of the intrinsic permeability of the geologic medium:

\[
q = k(\phi) f i
\]

(6)

where

- \( f = \gamma/\mu \)
- \( k = \text{saturation-dependent intrinsic permeability, } m^2 \)
- \( i = \text{fluidity of migrating fluid, } m^3/s \)
- \( \gamma = \text{specific weight of monitoring fluid, } Pa\cdot m^{-1} \)
- \( \mu = \text{viscosity of the migrating fluid, } Pa\cdot s \)

The gas-phase total head gradient is a function of the gas pressure gradient and, to a minor extent, the gravitational gradient. The intrinsic permeability tensor is a function of the water potential, \( \psi \).

More complex representations of the flow domain can be constructed by acknowledging the three-dimensional spatial complexity of fractured rock blocks separated by discrete fractures of finite areal extent. Dual porosity models are commonly used to simulate the interrelated flow between a fracture system and the surrounding rock matrix (see, e.g., Wang and Narasimhan, 1993; Updegraff et al., 1991). These models employ grids to discretize the flow domain into sets of cells representing both the fracture and rock matrix, with unique porosity and permeability distributions for each medium (Figure 28.4B). Such models become unwieldy, however, due to the large number of cells required to represent even a small rock volume.

Alternatively, boundary integral methods (see, e.g., Rasmussen et al., 1989; Rasmussen, 1991) can be used to reduce the dimensionality of the problem. The bound-
pore or core. Fractures may connect voids on the order of a meter and even a kilometer apart. Such long range connectivity makes laboratory and field-scale testing more difficult. Fractured porous media is even more difficult to characterize. The ability of water, air, and contaminants to migrate from a fracture into the rock matrix that bounds the fracture (and vice versa) can significantly affect their movement through the fracture. In situ characterization of a fractured medium is usually necessary to incorporate the scale of the heterogeneities inherent to the medium and to avoid the difficulty of removing and transporting a sample without major disturbance to the enclosed fractures. Because fracture transport properties may vary over large spatial scales (i.e., from tens to hundreds of meters or larger), field surface (Killbury et al., 1986) and borehole tests (Rasmussen et al., 1993) are useful for obtaining appropriate material properties.

Because borehole tests can be interpreted in many ways, depending upon the assumed geometry of the flow field and the assumed boundary conditions, significant effort should be expended in trying to understand the physical system near the borehole. Fracture locations and orientations can be mapped using oriented core collected during borehole drilling, or from downhole televiwer logs. Inclined boreholes (Figure 28.5) are preferred in areas where vertical fractures are the dominant flow channels of interest because vertical boreholes may not intersect and adequately sample the near vertical fractures (Rasmussen et al., 1993).

In addition, sloping boreholes allow a simple procedure for obtaining oriented core. An unevenly weighted cylinder with a marker on the leading end is slid down the borehole. The marker makes a chip in the end of the core stub remaining after the removal of the last core segment. If the marker is on the lighter side of the cylinder, the orientation mark will be on the top side of the stub. The next core segment removed is oriented by the mark at the top of the segment. If the rock is sufficiently competent, the core for an entire borehole can be oriented and the strike and dip of any intersected fractures can be logged. Core segments without fractures can be used for matrix characterization and the boreholes are available for downhole measurements.

Auxiliary data collected using boreholes to provide access to the rock mass may include water potentials (Anderson, 1987), water content (Elde, 1988; Andrews, 1983), temperature (Davies, 1987), air pressure (Smith, 1989), and electrical resistivity (Andrews, 1983; Thornburg, 1990) along the boreholes. These measurements can be used to identify zones of constant or varying material properties, and the spatial and temporal variations in these measurements may provide useful information regarding liquid and solute movement through the matrix and, by inference, through fractures. Evaluation of fracture conditions per se is constrained because of the limited volume associated with fractures in relation to the volume of the surrounding matrix.

Borehole field permeability tests using water and air can yield information on potential flow and transport characteristics (Tidwell, 1988; Rasmussen et al., 1993). While laboratory tests using core samples collected from boreholes may be adequate for obtaining matrix permeabilities, the combined fracture-matrix permeabilities can only be obtained through field measurements. Field experiments are conducted by isolating borehole intervals using packers, and injecting or extracting water or air into the interval. The length of the packers must be sufficiently long to assure that conducting channels within fractures do not bypass the packer and reconnect with the test borehole, thus confusing the interpretation of the test. A string of four packers (two above the test interval and two below) are often recommended to form guard intervals above and below the test interval (Figure 28.6). Pressures in the guard intervals are used to test for leaks from the test interval.

Figure 28.7 presents plots of field borehole vs. laboratory core measurements of permeabilities using both air and water permeabilities. It can be noted that only a poor correlation exists between the two due to the failure to account for fracture flow during laboratory tests. The figure also demonstrates the good relationship between permeabilities obtained using air and water. Saturated water permeability tests obtained from an initially unsaturated zone can be conducted by maintaining a constant water level within a single borehole, or in a specified borehole interval, and measuring the resultant water outflow.

Figure 28.8 presents a plot of the laboratory core and field borehole permeability tests using both air and water. Core data were collected using permeameters designed to measure air and water flow rates along the long axis of 6-cm oriented cores extracted at 3-m intervals from boreholes at the Apache Leap Tuff Site. It can be noted that the field-estimated saturated permeability distribution obtained using water compares reasonably well to the estimated distribution obtained using laboratory core segments. The higher permeability observed in the field can be attributed to the inclusion of fracture flow in the test. The field-estimated permeability using air is plotted at an ambient suction in the field of approximately 1 bar, which is inferred from laboratory moisture release curves and field neutron probe logs. The observed permeability distribution compares favorably with the laboratory-estimated values obtained from fractured core.

Air permeability tests may be conducted in a similar manner using single-hole techniques (Figure 28.9), but more useful information is obtained using either crosshole or dipole tests because of the larger effective volume (Trautz, 1984). In a crosshole test, one packed off borehole interval is used to inject (or extract) air, while other packed off intervals in the same or adjacent boreholes are used to monitor pressure response. Dipole tests are conducted by using two borehole intervals with one used for injection and the other for simultaneous extraction (Figure 28.9B). Crosshole and dipole flow tests using water are generally impractical in unsaturated fractured media because of the complex gravity force fields, as well as the relatively small spatial and large time scales of responses. Like field water injection tests, however, field air flow experiments are subject to ambiguity due to
the unknown geometry of the test region. For this reason, knowledge of the geologic conditions (e.g., fracture densities, locations, orientations, etc.) surrounding the borehole are critical for formulating the conceptual model.

If the principal conducting fractures are drained, the interpreted air permeability provides a good estimate of saturated water permeability. Because air flow tests are usually simpler to conduct and interpret than water flow tests in the unsaturated zone, this one-to-one relationship is extremely useful. No field method is currently available for measuring the water permeability of an unsaturated fractured rock, which is a serious constraint on site characterization. A method receiving increased attention (Tang, 1991) uses low-permeability geotextile membranes to impose a negative pressure on the rock surface. The method allows a positive pressure to be placed on the inside of a tubular membrane, which forces the membrane against the borehole wall. Because the head drop across the membrane is larger in magnitude than the applied interior positive pressure, the resulting fluid pressure is negative on the face of the membrane in contact with the rock. The unsaturated permeability can be calculated by knowing the conductance and flow across the membrane, along with the injection pressure.

Initial results from the Apache Leap Tuff Site indicate that gas tracer tests, either

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**Figure 28.8.** Apache Leap Tuff field and core permeability data using air and water as the test fluids.

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**Figure 28.9.** Test geometries for (A) single-hole injection/extraction and (B) dipole injection-extraction.
contaminant transport. The enhanced mobility of solute in the liquid phase of unsaturated fractured media is contrasted with the greater mobility of mobile, sorbed, and immobile phases, respectively.

Sampling strategies should acknowledge the complex nature of flow through unsaturated fractured media. Sample flow conditions, obtaining representative samples of the three-dimensional pore space, and determining the hydrodynamic response in the unsaturated fractured media. Sampling strategies should address the heterogeneity of the fracture network and the spatial and temporal variability of the flow and solute transport processes. Special attention should be paid to the role of fracture orientation, fracture aperture, and fracture connectivity in determining the transport properties of the unsaturated fractured media.

Sampling of the unsaturated fractured media involves the collection of pore fluids at specific locations within the fracture system. Sampling can be achieved by direct injection of a fluid into the fracture system, followed by the collection of the displaced fluid. This approach is suitable for sampling fractures with high permeability. Sampling can also be achieved by the use of passive samplers, such as diffusion devices or passive membrane samplers, which are placed in the fracture system and allow the collection of pore fluids over extended periods of time. These samplers are suitable for sampling fractures with low permeability.

Sampling of the unsaturated fractured media should be performed with careful consideration of the potential for contamination and the need for proper sample preservation. Sample preservation is crucial to maintain the integrity of the collected pore fluids and to ensure accurate analysis. Samples should be collected in clean, pre-rinsed sampling vessels, and the samples should be transported to the laboratory in a timely manner to minimize the risk of contamination. Sample preservation can be achieved by the addition of preservatives, such as acetic acid, to the collected samples. The samples should be stored at low temperatures to minimize the degradation of the collected pore fluids.
fluorescence. Many chemicals can be shown to fluoresce when excited with light (Goering, 1988). This phenomenon can be used to advantage by remotely monitoring downhole fluorescence. A laser generator is positioned on the surface, the laser beam is transmitted to any downhole location using a fiber optic cable, focused onto the borehole wall, and the amount of fluorescence is monitored using a downhole sensor (Figure 28.13). The intensity of the resulting fluorescence can indicate the presence of a specific compound on the borehole wall. An example of its application is determining the arrival time of an injected tracer at different depths along a borehole. The device can be left in the field at a specific location, or can be raised and lowered within the borehole to map specific tracer locations.

CALIBRATION AND EVALUATION OF UNSATURATED, FRACUTURED MEDIA MODELS

Water and air characterization data and chemical sample analyses are commonly employed to construct a conceptual or computer model of the flow regime. Inputs for matrix properties are usually obtained from laboratory tests, while fracture properties are determined using field tests. Calibration of the flow model can be accomplished using laboratory and field characterization data, reserving the chemical analysis data for model evaluation. In many circumstances, however, all available data must be used for model calibration due to the complexity of the geologic environment. Model evaluation should then be accomplished by conducting an independent field test that consists of flow conditions dissimilar to previous tests. The field test should be modeled a priori using calibration data sets, and a prediction forecast should be generated. The field test should be designed to test all components of the conceptual model in such a way as to assure that the results of the test
unambiguously resolve assumptions central to the model. Computer modeling can be performed prior to conducting the test for the purpose of identifying field tests that provide the most useful information. Especially useful tests generally involve coupled flow and tracer tests in the vertical direction that incorporate both matrix and fracture flow components.

This evaluation exercise requires that parameter, model, and experimental uncertainties be quantified prior to the design of the experiment. Parameter uncertainties should be estimated based on repetitive measurements of rock fracture and matrix properties. The spatial variation in material properties cannot be determined by assessing the variation of samples collected over a range of distances. Quantification of experimental uncertainties requires that instrument and monitoring uncertainties be determined to assess the importance of measurement errors. Propagation of parameter and experimental uncertainties can be used to provide simulation forecast confidence intervals. The result of the field experiment can then be compared to the prediction interval to provide a rigorous test of model performance. Figure 28.14 summarizes the use of uncertainties in the model evaluation process.

**FURTHER INFORMATION**

Essentially all of the technical papers on flow and transport through unsaturated fractured rock have been published during the last ten years as the result of interest in the potential emplacement of high-level radioactive waste in a geologic repository located in unsaturated fractured tuff. An additional source of information is also available in the petroleum literature. Also, there has been an increased realization that many contaminated sites and proposed waste disposal sites involve flow and transport through unsaturated fractured rock and that improved understanding and assessment techniques are required. For a general coverage of the topic, see the American Geophysical Union monograph edited by Evans and Nicholson (1987). For a description of unsaturated fractured rock testing procedures and data sets, see Rasmussen et al. (1990) and Rasmussen et al. (1993). Evans (1983) and Rasmussen and Evans (1986) provide a general discussion of unsaturated flow and transport monitoring techniques. A summary of fracture flow models can also be found in Mercer et al. (1983) and Bear et al. (1993).

**REFERENCES**


