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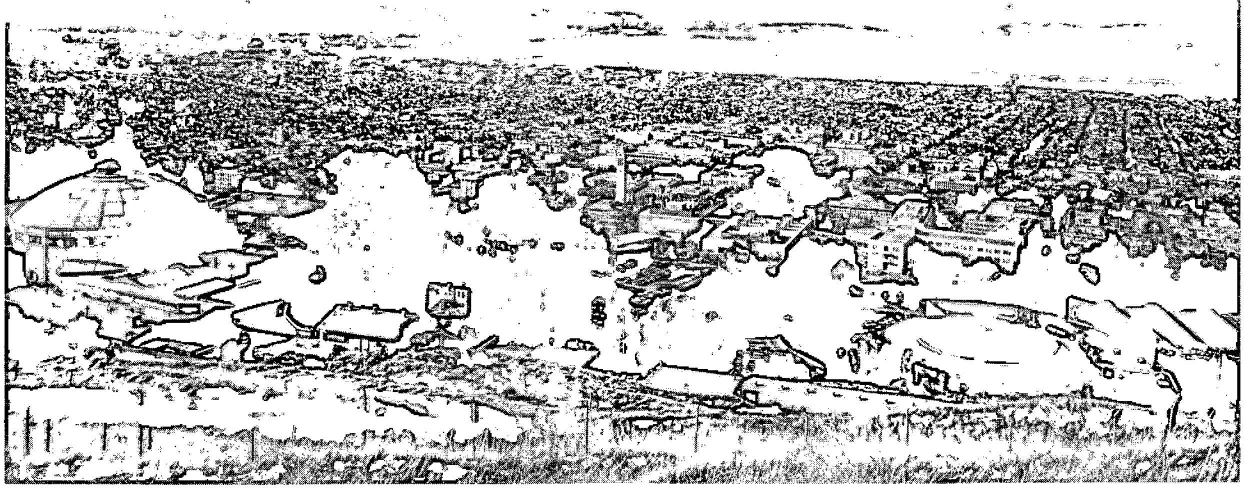

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Summary

The history of the development of techniques for determining equivalent rock mass permeability from discrete fracture data is reviewed. These techniques began with conceptual models which considered all fractures to be infinitely long. Because fractures are in fact finite, the equivalent permeability tensor computed by this approximation may not be applicable. Recent studies of the definition of an equivalent permeability tensor for networks of fractures with finite lengths are reviewed, and field techniques which show promise for obtaining in situ measurements of fracture length are presented.

Introduction

Transport by moving groundwater is the most likely means of escape for nuclear waste from a repository. Groundwater flux is determined by the permeability of the rock and by the gradient. For the purposes of this paper, we will emphasize determination of equivalent porous medium permeability of large rock masses, specifically as related to fractured crystalline rock. Permeability in fractured rock is controlled mainly by individual fractures which are heterogeneously distributed throughout the rock mass. As a result, groundwater movement can be very complex and difficult to predict. A number of important questions may be posed regarding equivalent permeability. First, how do we determine if it is appropriate to use equivalent properties rather than the discrete fractures? Then, how do we determine what the equivalent permeability of a rock mass is? Further, if the equivalent permeabilities can be determined on the basis of limited samples of fractures from boreholes or a shaft, how can we anticipate the effect of major, unsampled fracture conduits that may jeopardize the containment of nuclear waste?

Historical Development

Snow's Method

Snow introduced the concept of representing the permeabilities of single fractures as matrices.[1] The basic approach used in calculating directional permeabilities of a fracture system is discussed below, and follows that of Snow. For single-phase, non-turbulent flow of an incompressible Newtonian fluid, the parallel plate analogy for flow through a fracture is:

$$q = \frac{(2b)^3}{12\mu} \rho g I \qquad (1)$$

where:
q = discharge per unit width of conduit — L^2/T
$2b$ = fracture aperture — L
ρ = fluid density — M/L^3
g = acceleration of gravity — L/T^2
I = effective potential gradient — -
μ = fluid viscosity — M/LT

Snow defines flow in a single conduit under a general field gradient as:

$$q_j = -\frac{(2b)^3}{12\mu} \rho g \, (\delta_{ij} - n_i n_j) \, I_i \qquad (2)$$

where:
q_j = discharge vector per unit width of conduit — L^2/T
δ_{ij} = kronecker delta
$n_i n_j$ = direction cosines of normal to fracture plane — -
I_i = potential gradient vector — -

Snow further assumes that the gradient I_i is felt uniformly throughout the fracture system and that all fractures completely transect the elementary study volume and maintain constant aperture and orientation. Under these conditions, the permeability tensor for the network of fractures is formed by adding the respective components of the permeability tensors for each individual fracture. Thus:

$$k_{ij} = \frac{1}{12} \sum \frac{(2b)^3}{S} (\delta_{ij} - n_i n_j) \qquad (3)$$

where
k_{ij} = intrinsic permeability tensor for fracture network — L^2
S = spacing between fractures of same orientation — L

Hydraulic conductivity is related to intrinsic permeability through the properties of the fluid. Thus:

$$K_{ij} = \frac{\rho g}{\mu} k_{ij} \qquad (4)$$

where K_{ij} = hydraulic conductivity tensor. — L/T

The permeability tensor of a rock mass at a given sampling station is obtained by summing the tensors from the individual fractures.[2] Where more than one sampling station is used, the average of all the stations is calculated. Having obtained the permeability tensor for a given rock mass, one can then determine the principal components of the tensor and their directions.

This is equivalent to finding the eigenvalues and eigenvectors of the tensor, which provide the magnitudes and directions of the principal permeabilities.

A schematic drawing of the conceptual field approach to Snow's method is shown on Figure 1. Fractures are assumed to be extensive and planar throughout the study volume, and apertures are assumed to be constant. Apertures and orientations are measured along sample lines and the resulting directional permeabilities are computed and summed. This method was applied by Bianchi and Snow to fractures exposed on a rock outcrop.[2] The fractures were mapped along line samples to get orientation data, and aperture data were obtained by optical methods. The assumption that all fractures completely transect the study volume is considered to be a significant limitation to Snow's method. Real fractures can be truncated within the study volume and only conduct significant volumes of fluid if they are connected to other fractures. The symmetric permeability tensor predicted by Snow's method may not be applicable.

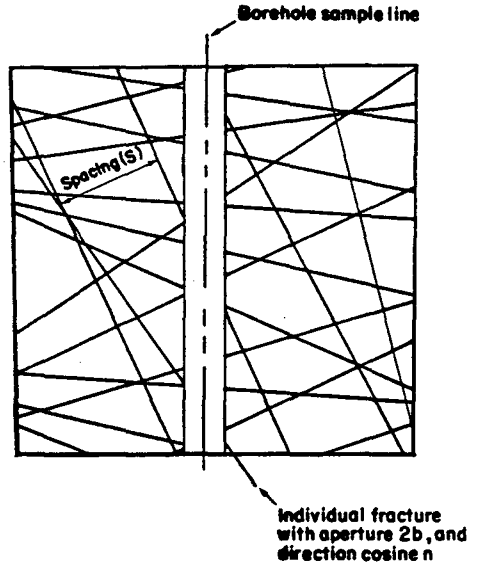

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Fig. 1. Conceptual fracture model for application of Snow's method to determining rock mass permeability.

Field Studies in the Stripa Granite

Snow's method formed the initial basis for Lawrence Berkeley Laboratory's hydrology work in the Stripa granite in Sweden. The Stripa project was developed to evaluate field techniques for rock mass characterization for high level nuclear waste disposal. A multi-faceted approach shown schematically in Figure 2 was formulated to obtain the appropriate discrete fracture data to compute equivalent rock mass permeability.[3] Means were devised to measure apertures, orientations, and spacings of fractures variously from oriented boreholes, surface outcrops, and subsurface excavations. Investigations of surface outcrops, studies of oriented boreholes and cores, and borehole television logging were designed to determine the fracture system geometry. The fracture apertures were obtained by borehole

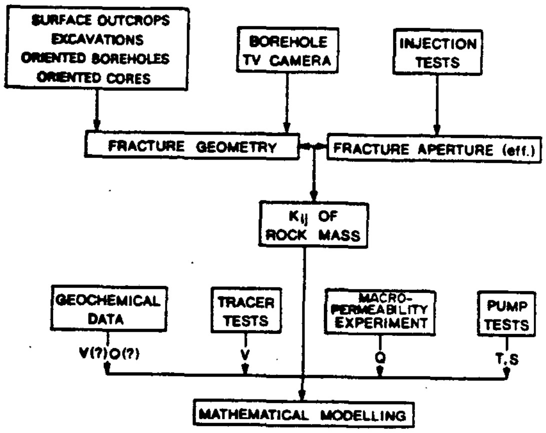

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Fig. 2. Flow chart for data input to the determination of rock mass permeability for the Stripa Project.

injection tests on very close spacing. These tests were to provide all of the data required for calculation of rock mass permeability by Snow's method. This permeability would then be directly verified by a single macropermeability experiment, a large scale measurement of the permeability of some 200,000 m^3 of rock.

Borehole Studies. The boreholes which would provide the primary data base for permeability determination at Stripa are shown in Figure 3. These consisted of three holes from 320 to 360 meters in length drilled from the surface at angles of 45° to 50° from the horizontal. The boreholes were oriented to intersect the major fracture sets at the site and thereby provide representative samples of each set. The boreholes were tested using constant pressure injection techniques at 2 meter intervals. An example of the test results from borehole SBH-2, computed in terms of equivalent porous medium hydraulic conductivity, is shown in Figure 4.

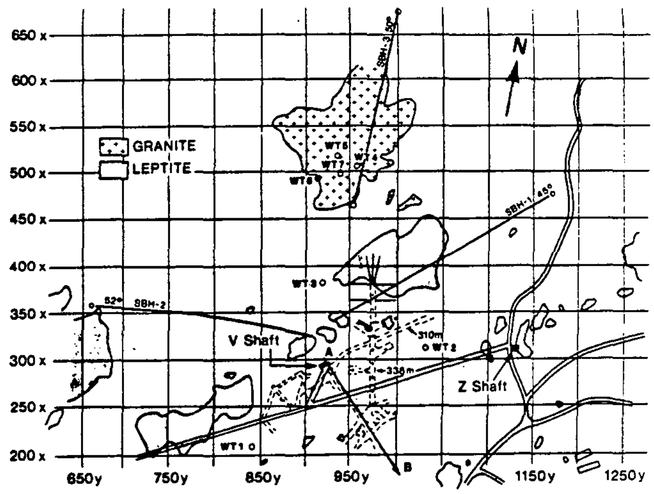

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Fig. 3. Locations of surface boreholes and underground test area at the Stripa Test Station.

These results range over six orders of magnitude and demonstrate the extreme degree of heterogeneity which can arise in permeability measurements on the scale of a 2 meter test interval.

The high conductivity test intervals in Figure 4 reflect the presence of a few relatively large aperture fractures among many smaller fractures. Given the orders of magnitude difference in permeability observed in the data, the presence of only one large aperture fracture in a sample can significantly change the computed

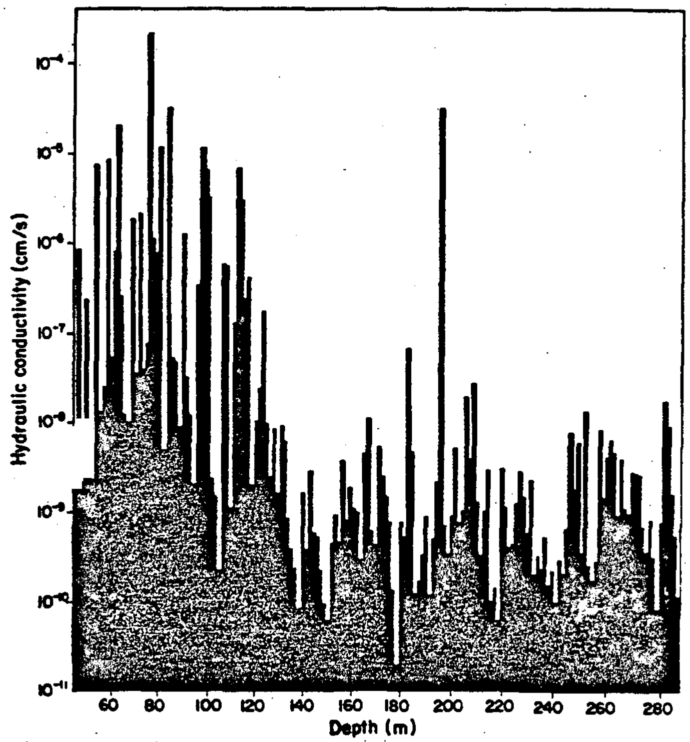

Fig. 4. Equivalent porous medium hydraulic conductivity values obtained from sequential injection tests over 2 m intervals in borehole SBH-2. Tests performed in leptite and Stripa granite at the Stripa Test Station.

bulk properties of the rock mass. These rare but hydrologically significant large aperture fractures could potentially play a very important role in waste isolation. There is a relatively high probability of large aperture fractures being present in the rock mass but not included in the data base. Therefore, it is important to develop estimates of rock mass permeability from statistical distributions based on observed data, rather than directly on the observations themselves.

Macropermeability Experiment. As mentioned previously, a large scale macropermeability experiment was also performed at Stripa to provide a basis of comparison for the integrated results of the small scale borehole tests. This experiment involved measuring the groundwater seepage into an isolated 33 m long drift at the 336 m level of the Stripa mine as the moisture pickup of the ventilation system. A schematic of this experiment is shown in Figure 5. The drift was isolated by a vapor-tight bulkhead and warm air was circulated into and out of the enclosed portion. The ventilation system was adjusted to evaporate water at the rate it entered the drift, thus maintaining the drift in an essentially dry

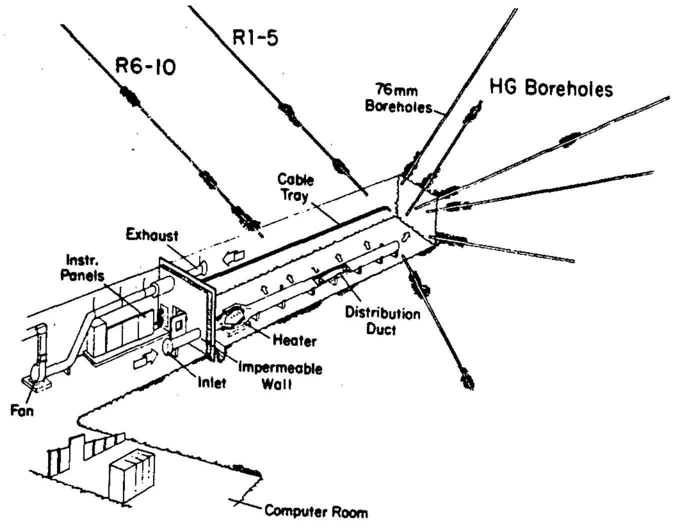

Fig. 5. Schematic drawing of the macropermeability experiment for measuring large scale rock mass permeability at the Stripa Test Station.

state. By monitoring the moisture content of the incoming and outgoing air, the total seepage rate into the tunnel could be obtained. Water pressures were measured concurrently within the rock surrounding the drift. Pressures were monitored in a three-dimensional array of 15 boreholes, ten of which were radial and five extended off the end of the drift. Packers were used to isolate six monitored zones within each borehole at distances ranging from 5 m to 40 m from the walls of the drift. Water pressure was measured in each zone by dial gauges mounted outside the drift. Each experiment was allowed to continue until both the groundwater seepage and pressure approached equilibrium.

An example of water pressure data from the macropermeability experiment is presented in Figure 6. This figure shows a semi log plot of hydraulic head versus distance from the axis of the drift as measured in the radial boreholes. In theory, a plot of this type should yield a straight line for radial flow in a homogeneous, isotropic porous medium. The data from several of the individual boreholes and the weighted average results of all radial boreholes yielded surprisingly good straight lines. The weighted average hydraulic conductivity of the rock surrounding the drift was computed to be 1.0×10^{-8} cm/s, which was in reasonable agreement with the average equivalent hydraulic conductivities obtained from small scale tests in the surface boreholes. Additional information about the macropermeability experiment is presented by Nelson and Wilson.[4]

Conclusions from the Stripa Work. Although data analysis of the Stripa results has not been completed, the general approach of approximating large scale behavior through the integration of the results of large numbers of small scale tests looks promising. Increased confidence in the method must be gained through application at other sites, together with further refinements in methodology. For example, the macropermeability test has demonstrated that large scale tests can be designed to directly measure equivalent porous medium properties in an inherently discontinuous rock mass, but it was not clearly demonstrated

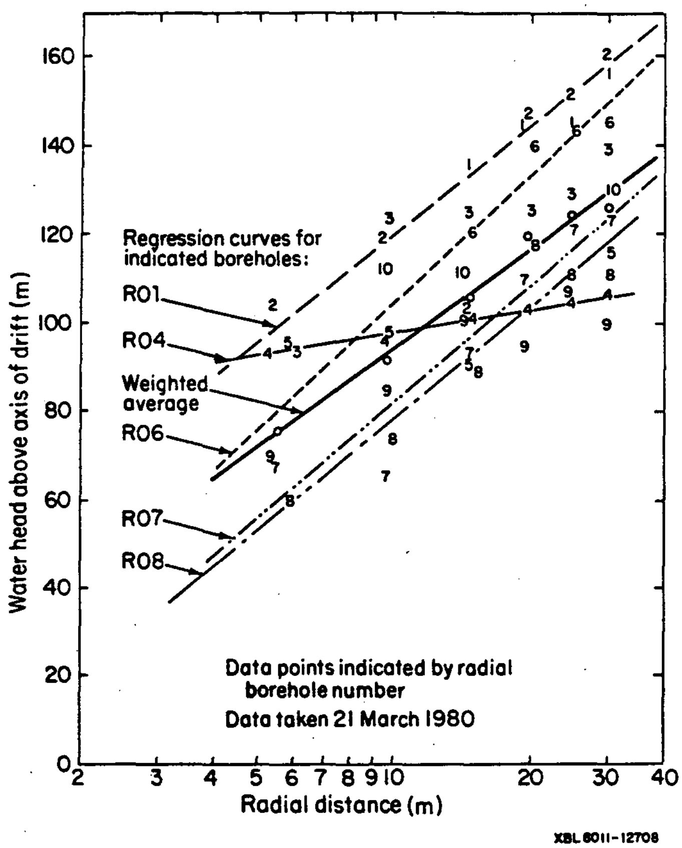

Fig. 6. Water pressure data from ten radial boreholes in the macropermeability experiment at the Stripa Test Station.

that this volume was large enough to be statistically representative of the rock mass. Large fractures may exist in the rock mass such that the macropermeability experiment, if performed at a different location, could have yielded a considerably different result. One such fracture zone was recently encountered at a depth of about 800 m in a borehole drilled from within the mine. The inflow from this zone was initially about 55 ℓ/min, which increased the inflow to the entire mine by some 10 percent.[7] After about three months this flow rate had dropped to about 40 ℓ/min. These flows were in excess of anything that had been measured from a single fracture zone in any previous investigation at Stripa.

Could the existence of a potentially high permeability zone such as that mentioned above have been predicted based on the previously gathered data at Stripa? If it were assumed that the existing data base had included the complete range of possible hydraulic behavior, the answer would be negative. However, if the closely spaced data were used to generate probability density functions for the geometric parameters of fractures, extrapolation of these functions could be used to anticipate the occurrence of fractures that were not observed in the sample.

An example of the statistical treatment of data is presented in Figure 7. This figure shows a log normal probability plot of apertures from borehole SBH-2 at the Stripa Test Station. These apertures were computed by assuming that test results were governed by the largest fracture in each 2 m test interval. The linearity of this plot indicates good conformance of the data to a

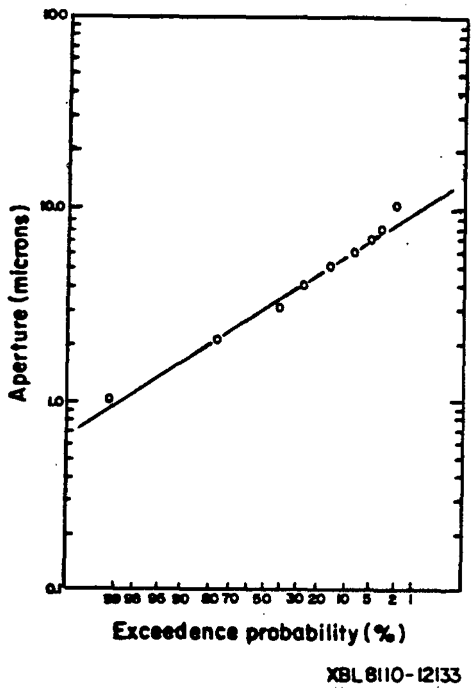

Fig. 7. Lognormal probability plot of fracture apertures inferred from borehole SBH-2 at the Stripa Test Station. Data are for fractures in granite encountered at depths exceeding 140 m.

lognormal distribution, which is in agreement with the earlier conclusions of Snow.[5] This lognormal distribution could be used in conjunction with distributions for the other geometrical parameters of fractures, such as length, spacing, and orientation, to randomly produce statistically relevant fracture systems. These generated fracture systems would then be studied to evaluate the range of behavior which might be expected from samples of a given volume within a given rock mass.

The probability density functions which are currently thought to best represent the parameters of fracture length (or area in three dimensions), fracture spacing, and fracture aperture, are shown on Figure 8. These are all very strongly skewed distributions, implying that many fractures exist with small lengths, spacing and apertures, but that very few exist with large values of these parameters. It is these less common, larger fractures which pose the greatest threat to geologic containment of nuclear waste.

Rock Mass Behavior for Fractures of Finite Length

Application of a stochastic approach to determining the permeability of a rock mass with fractures of finite length might be done in the following way. Statistically representative samples of the geometric parameters of the fracture system would be taken at a field site and the probability density functions for the parameters determined. The density functions could then be used in a controlled sampling scheme to create synthetic fracture networks that represent the range of possible behavior of the rock mass. This study would emphasize the role of large fractures that may not have been sampled, but might be present in the rock mass.

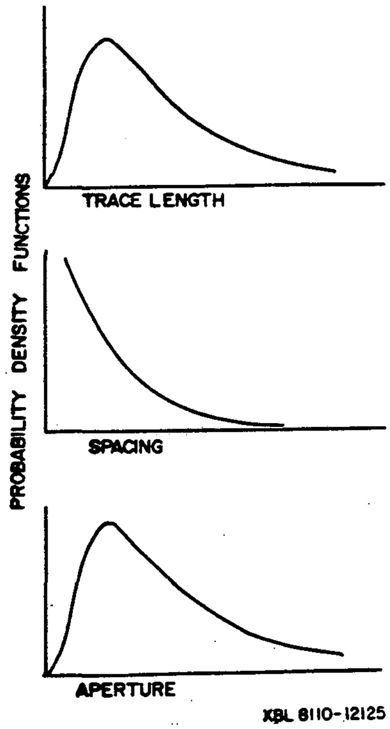

Fig. 8. Probability density functions currently considered to best represent the principal parameters controlling fracture geometry.

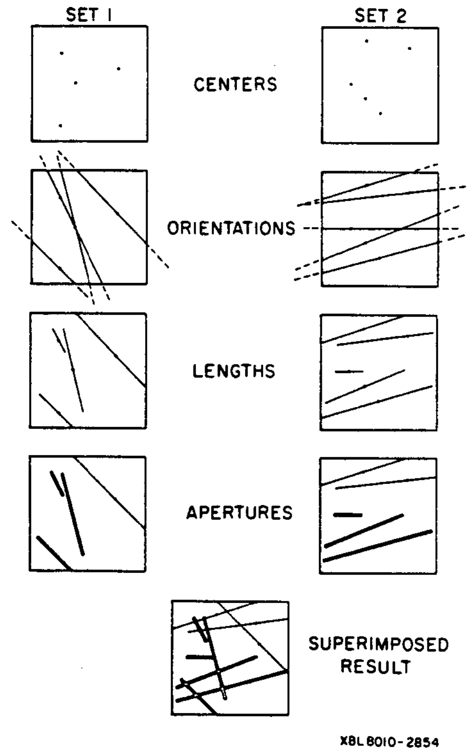

Fig. 9. Generation of hypothetical fracture system from statistical data.

Numerical Techniques for Network Analysis

Figure 9 shows how a statistically representative model of the fracture system is being studied in two dimensions at LBL.[6] The process begins with the generation of separate random centers for each set of fractures within a two-dimensional area. The number of random centers will govern the density of fractures for each set. A fracture is then located through each center, and an orientation is assigned by randomly sampling from the statistical distribution of orientations for the particular set. Each fracture is then assigned a length from a statistical distribution of fracture lengths. Apertures are then assigned in a similar fashion. The groups of fractures generated for each individual set are then superposed and the result is a fracture network which has the same statistical properties as the fracture system measured in the field. An important advantage of this approach is that the artificially generated system may contain fracture sizes that were not observed in the field.

Artificially generated fracture systems can be used to investigate the range of behavior which might be expected from the rock mass, and are particularly valuable for identifying the likely characteristics of a representative elementary volume (REV) for the rock. The REV is the minimum volume of rock which contains a representative sample of heterogeneities. If an REV can be identified which exhibits continuum behavior, then it may be possible to accurately use a porous medium model which averages the contributions of all the fractures and treats the rock mass as a continuum.

An example of how artificially generated fracture systems can be used to identify an REV is shown in Figure 10. In the upper left hand

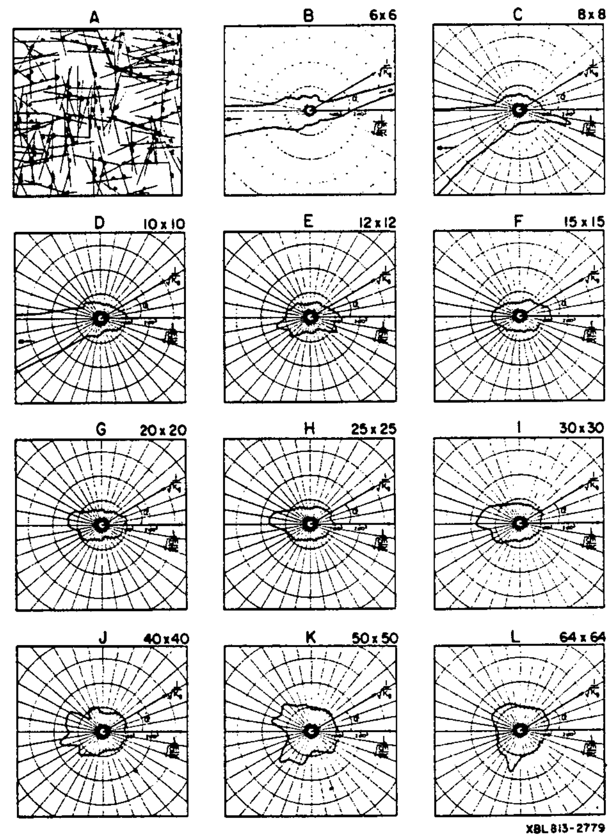

Fig. 10. Example of procedure for identifying a representative volume for systems of finite fractures.

corner of that figure is shown a numerically generated fracture system. This system consists of two sets of fractures with mean orientations at right angles to one another and identical apertures in all fractures. This type of fracture system was chosen for this example because the correct equivalent porous medium permeability "ellipse" will be a circle. The REV for a given density of fractures is identified by sequentially testing larger and larger volumes until there is no change in the size or shape of the "ellipse." The fracture network can be approximated by a continuum when the plot assumes an elliptical, or in this case, a circular shape. The size of the study area is 100 x 100 units. Sample sizes commence with a 6 x 6 area in the upper portion of Figure 10, and culminate with a 64 x 64 area in the lower right corner. The permeability "ellipsoids" are very irregular for the smaller sample volumes, but gradually assume a more regular shape for the larger volumes and approach the expected circular shape in the largest volume.

The example in Figure 10 demonstrates the potential which now exists for using statistical data from real fracture systems to identify the characteristic of REV's. However, if we find in our studies that there is no appropriate REV due to the extreme variability of the fracture systems or the specific nature of the problem to be studied, we can use a fracture generation technique to study, perhaps in a controlled Monte Carlo fashion, fracture systems that might exist at the repository site. Such studies can have great value for risk analyses and leakage scenario development.

Field Techniques for Data Acquisition

Having created a model for handling fracture statistics in generating possible networks at a site, we are now confronted with the problem of how to obtain field data to put into the model. Orientation of fractures and apertures can be obtained from borehole tests and mapping techniques. However, the size of the fractures and their density are much more complicated. Size and density determine the degree of interconnection with other fractures and therefore are critical parameters. A promising approach to this problem involves the detailed analysis of transient well test data to identify boundary conditions of individual fractures. Water is injected at constant pressure into a single fracture which has been isolated in a borehole by packers as shown in Figure 11. The flow rate curve which results from this test has a form that may interpreted in terms of the permeability of the rock, the stiffness of the rock, and the fracture length, aperture, and interconnection.

Figure 12 shows the general form of a transient flow rate curve which can result from a constant pressure injection test. The first part of the curve is called the infinite region, where the pressure front of the injection has not yet reached the boundaries of the fracture. It is so named because it follows the theoretical curve for an infinitely long fracture. This portion of the curve can be interpreted to determine the aperture of the primary fracture intersecting the wellbore fracture and the stiffness of the rock. This method yields the hydraulically effective aperture which the optical method cannot provide. The flow rate

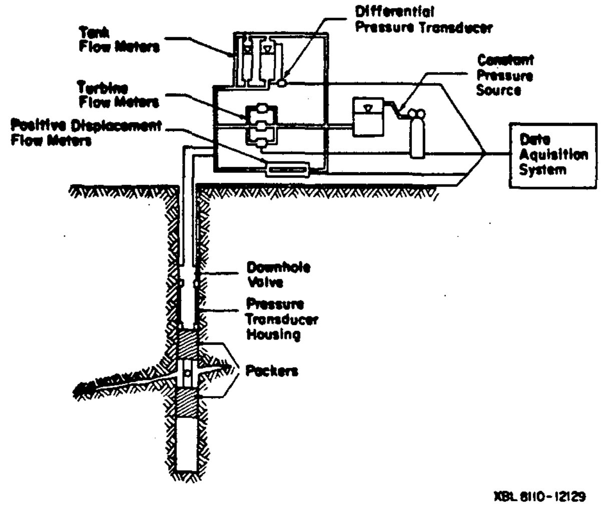

Fig. 11. Schematic drawing of a constant pressure injection test of a single fracture.

curve starts out steeply and gradually levels off. As the pressure front from the injection reaches the edge of the fracture, the flow rate begins to drop off. This is called the depletion portion of the curve, by analogy with terms used in reservoir engineering, and provides information about the length of the fracture.

After a period of depletion, the flow rate may level off again. This portion of the curve is called the leakage, and reflects flow into other fractures or into the rock itself. The observation of transient flow rate curves of this general shape in field tests lends support to this general approach. Leakage curves presently being used are based on the assumption of uniform flow into a porous matrix. Thus from the transient flow rate curve we can potentially obtain data for the aperture of the primary fracture, and learn something about fracture size and the nature of fracture interconnection. As

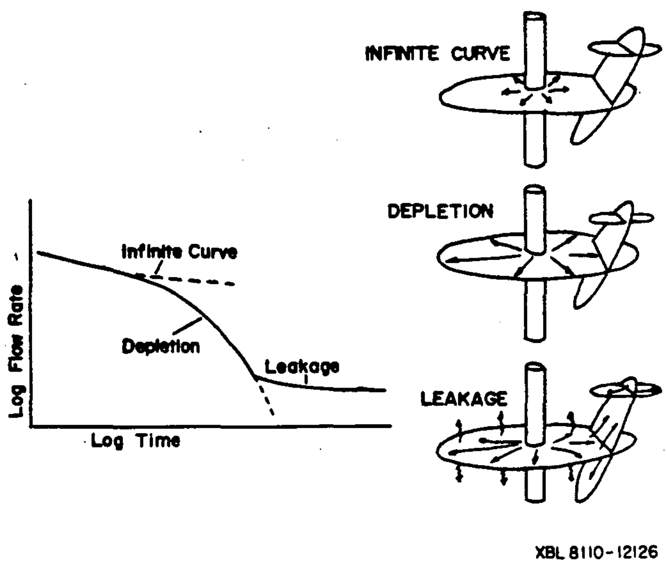

Fig. 12: General form of a transient flow rate curve from a constant pressure injection test of a single fracture.

with any type curve approach, however, interpretations are based upon a simplified conceptual model which may not be appropriate for all data. Nonetheless, the approach discussed here does appear to have the capability of providing at least limited data on the difficult parameter of fracture length for use in generating representative fracture network models.

Conclusions

Current research is directed toward developing techniques for identifying equivalent rock mass permeability which take into account finite fracture lengths. For an actual repository site it is proposed that detailed measurements be made of the apertures, lengths, orientations and densities of fractures from well tests. This data can then be used to generate fracture networks that are statistically representative of a given site. After the fracture networks have been studied to estimate the hydrologic properties of the site, large scale tests should be conducted in a test facility at repository depth and eventually in the repository itself to verify the predictions. Specifically, groundwater pressure around the workings and water inflow into the workings should be monitored. These data will provide an important verification for earlier estimates of the hydrologic properties of the site.

Acknowledgement

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