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Fluid flow through single fractures

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ABSTRACT: A stratified percolation model is used to analyze saturated and unsaturated fluid flow through single fractures and the scaling behavior of saturated fluid flow through single fractures. The stratified percolation model simulates experimentally observed correlations in fracture flow path geometry. Using percolation theory and the principle of conservation of volume, deviations from cubic law behavior for fluid flow through single fractures result from a nonlinear relationship between apparent aperture closure (from farfield displacement measurements) and void aperture closure. From the analysis of unsaturated fluid flow in a fracture, it was found that non-wetting phase permeability decreases rapidly with increasing wetting phase saturation. Also, the cross-over in permeability of the wetting and non-wetting phases is essentially invariant with stress. Renormalization group techniques are applied to investigate the dependence of fluid flow through a fracture on sample size.

INTRODUCTION

A major challenge in the analysis, design and building of underground structures is to understand how changes in effective stress affect the hydraulic properties of a fractured rock mass. The key to understanding the hydraulic, mechanical and seismic properties of natural fractures is to quantify the topology of the void spaces in fractures and understand how fluid flow and deformation properties are coupled through this topology. In addition, by understanding the fracture topology, an indication can be obtained of how fluid flow and deformation properties scale with different sizes.

Fluid flow through a fracture is fundamentally different than fluid flow through a porous medium. In a fracture, fluid flow occurs in roughly a two-dimensional plane and is controlled by the distribution of apertures. The complex flow paths of a fracture arise because a natural fracture consists of two rough surfaces in partial contact. Between the areas of contact, there exist voids of variable geometry and aperture. If a fracture is placed under stress, the fracture voids deform, resulting in an increase of contact areas, a reduction of void aperture and a reduction in fracture void volume. The void geometry of a fracture will be influenced by the roughness of the individual fracture surfaces and the correlations between the two surfaces (Swan, 1983; Brown et al., 1986). Other investigators have made measurements of fracture contact area (Iwai, 1976; Bandis et al., 1983), fracture flow path geometry (Pyrak-Nolte et al., 1987; Gentier et al., 1989), and size and distribution of fracture apertures. The basic result of all these studies is that void geometry is variable in size and shape, and the geometry of the voids determines fluid flow through the fracture and fracture deformation.

A standard approach has been to model fluid flow through a fracture as if it were between parallel plates. In this approach fluid flow through the fracture is proportional to the cube of the aperture of the fracture ("cubic law"). Several investigators have made measurements of fluid flow through both induced and natural fractures and found relationships between flow and aperture much greater than cubic (Iwai, 1976; Engelder and Scholz, 1981; Raven and Gale, 1985; Pyrak-Nolte et al., 1987). These deviations from cubic law behavior have been attributed to variable void cross-section (Engelder and Scholz, 1981) or to surface roughness and flow path tortuosity (Tsang, 1984).

Few investigators have examined the effect of scale of observation on fluid flow through fractures. Experimental evidence (Witherspoon et al., 1979; Raven and Gale, 1985) showed opposing trends, with hydraulic conductivity increasing or decreasing with increasing sample size. From a numerical investigation, Neuzil and Tracey (1981) concluded that smaller specimens will have smaller values of conductivity than larger specimens under the same stress because fewer large flow channels exist. From a theoretical study of the effect of sample size on the hydraulic and deformation properties of a fracture Tsang and Witherspoon (1983) determined that large scale roughness of the fracture controls the hydraulic and mechanical properties of the fracture. They concluded that if the rock specimen is smaller than the large scale roughness wavelength then the fluid flow measurements made on the specimen will not be representative of the large fracture behavior.

MODEL DESCRIPTION

Examples of the flow path geometry in a natural fracture at three different stress levels are shown in Figure 1. Flow paths are white while the contact areas are black. At the lowest stress (Fig. 1a) the contact area appears as isolated "islands" of contact. At high stresses (Figs. 1b and 1c) these areas of contact become "continents" with "lakes" of metal connected by filamentary tortuous "streams" of metal. These images show that the distribution of voids and contact areas are heterogeneous but correlated. Thus, a void site has a high probability of being surrounded by other void sites, and, conversely, a point of contact has a high probability of being surrounded by other points of contact.

We have chosen a stratified continuum percolation model to investigate fluid flow (saturated and unsaturated) in fractures, the change in fluid flow with stress in fractures, and the effect of sample size on saturated fluid flow through fractures. This model (Nolte et al., 1989) incorporates the randomness of standard continuum percolation and the scaling nature of fractals, and reproduces the type of flow geometry observed in experiments. A continuum model is used because the distribution of void apertures is continuous and there is no underlying lattice structure in a fracture.

To model the flow path geometry, a pattern is generated by placing N random sites within an area called a tier. Each one of these sites represents the center of a new tier which is smaller in size than the preceding tier by a scale factor b. In each of the new tiers, N sites that define the center of yet another series of tiers, which are smaller than the preceding tier by the same scale factor b, are again randomly distributed. This process can continue for as many tiers as desired. The final result is a correlated pattern. The pattern in Fig. 2a represents a fracture under low stress because of the small amount of contact area (white areas in Fig. 2). This pattern was generated using a five tier model with twelve points per tier and a scale factor of 2.37 between tiers.

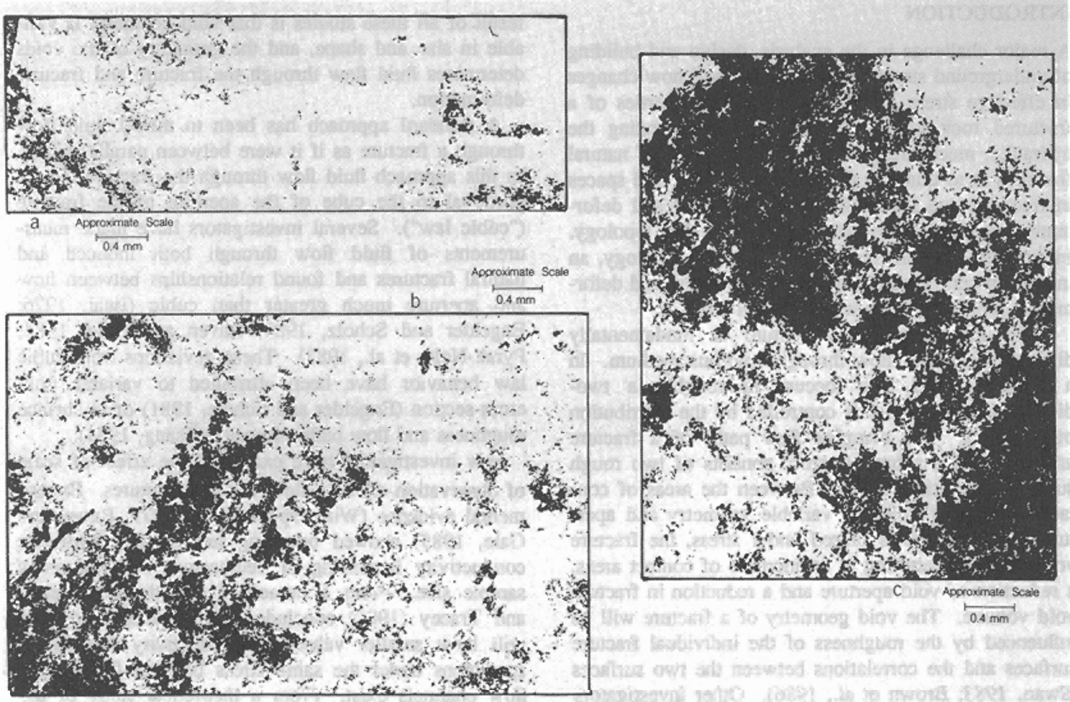

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Fig. 1. Composite micrograph of a portion of a natural fracture at effective stresses of (a) 3 MPa; (b) 33 MPa; and (c) 85 MPa. Black represents contact area and white flow paths.

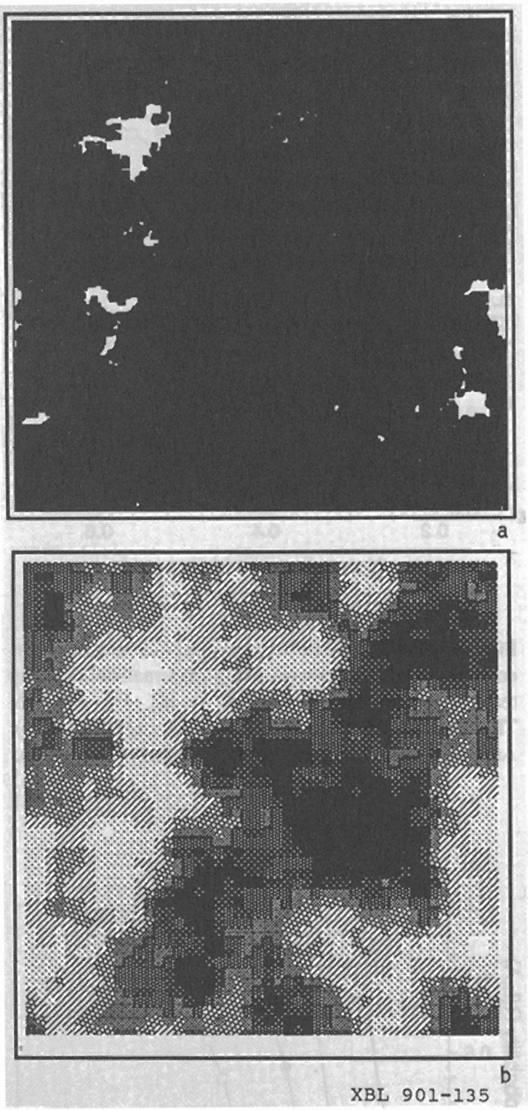

Fig. 2. A stratified continuum percolation model of void spaces in a fracture under low stress; (a) Black represents void spaces and white represents contact area, the fractal dimension of the flow paths is D = 1.99; (b) aperture contour plot of pattern in (a) white regions represent contact area, and increasing shades of gray to black represent increasing aperture. Scale of contour: 20 units of aperture.

On the final tier, as the points are being plotted to construct the pattern, points will overlap. The amount of overlap that occurs at each pixel of the pattern is counted and equated to fracture aperture (arbitrary units). The aperture distribution of a generated pattern is related to the density of sites in the construction of the pattern. Figure 2b is a map of the aperture distribution of the pattern shown in Figure 2a. White areas in Figure 2b represent contact areas, and black areas represent sites of largest apertures. It is observed that the aperture distribution is correlated; that is, sites of large apertures have high probability of being surrounded by other sites of large apertures.

SATURATED FLUID FLOW AND MECHANICAL DEFORMATION

Previously, measurements of mechanical displacement and fluid flow through three different natural fractures in samples of quartz monzonite were carried out (Pyrak-Nolte et al., 1987). The fluid flow data were found to deviate from "cubic law" behavior and to show a dependence on apparent mechanical aperture much greater than cubic.

Pyrak-Nolte et al. (1988) found that deviations from cubic law behavior can be explained by assuming: (1) cubic-law dependence of flow on the actual local aperture at the microscopic level; (2) conservation of rock volume when deforming the fracture; and (3) macroscopic flow properties are dominated by the critical neck (the smallest aperture along the path of highest aperture through the fracture). These assumptions were applied to fracture flow path geometries generated from the stratified percolation model. The apparent mechanical aperture (far-field displacement) of the pattern was determined using a zeroth order approach assuming that rock volume is conserved during fracture deformation. If the void space is reduced one unit of aperture, the material in the asperities does not simply vanish or interpenetrate into the opposite fracture surface. Thus, the far-field displacement is not equal to aperture closure but instead to some fraction of the aperture reduction, depending on the relative area covered by asperities. By assuming conservation of volume, a nonlinear relationship exists between apparent aperture and void aperture closure which depends upon the topology of the void space and areas of contact. The amount of void aperture closure is greater than the amount of mechanical displacement. This results in the critical neck being closed faster than the apparent aperture.

The non-linear relationship between the apparent aperture and void aperture closure is important to understanding the relationship between fluid flow through the fracture and changes in apparent fracture apertures. Deviations from cubic law behavior would not exist if fluid flow through the fracture depended on the apparent mechanical aperture, or if the apparent mechanical aperture and void aperture closure were equal. However, because of the non-linear relationship between apparent mechanical aperture and void aperture closure, deviations from cubic law behavior arise.

SCALING BEHAVIOR OF SATURATED FLUID FLOW

A major practical problem in studying the flow of fluids through geologic formations, is how to relate laboratory measurements to behavior in the field. Laboratory measurements are performed on relatively small samples with sizes on the order of a few centimeters up to, perhaps, a meter, while flow through geologic formations may occur over kilometers. Do the laboratory measurements have anything to do with macroscopic behavior, or do different mechanisms dominate at different scales? Can hydraulic measurements performed in the laboratory on core samples be used to quantitatively predict behavior in situ? One step towards solving this dilemma involves the use of renormalization techniques. Renormalization group theory deals specifically with the question of how the physical properties of random patterns scale with the size of observation (Pfeuty and Toulouse, 1977). More specifically, renormalization techniques can be applied easily to percolation problems to quantify the size dependence of percolation probabilities.

We have appled these renormalization techniques to our model of stratified continuum percolation through single fractures. The two properties to study are the spanning probability, R(L,A), and the size of the spanning cluster, P(L,A). The spanning probability is the probability that a continuous flow path will span a sample of size L for a specific void space area. The strength of the spanning cluster is the fraction of the void space area that belongs to a spanning flow path. The renormalization procedure to determine these two probabilities is simple: divide a flow path pattern into subsections of size L, and count how many of the subsections have a spanning flow path. Divide this number by the total number of sections to obtain R(L,A). For those sections that do have a spanning path, count the fraction of the void space area which belongs to that flow path, to yield the probability P(L,A). The results from Monte Carlo simulations for R(L,A) and P(L,A) are shown in Figure 3 and Figure 4 for stratified continuum percolation patterns with three tiers.

The spanning probability R(L,A) has the important feature that the probability is invariant of sample size at the percolation threshold (Fig. 3). This is called fixed point, and provides a direct method to determine percolation thresholds. Stratified percolation has the useful property that the percolation threshold remains invariant when expressed using the area fraction per tier (Nolte, 1989). Below the threshold, the percolation probability decreases with increasing sample size. The opposite is true above the threshold: the percolation probability increases with increasing sample size. These opposite trends can create confusion when experimental results from different samples or different sizes are compared.

The size of the spanning cluster P(L,A) rises sharply with increasing void space coverage (Fig. 4). The

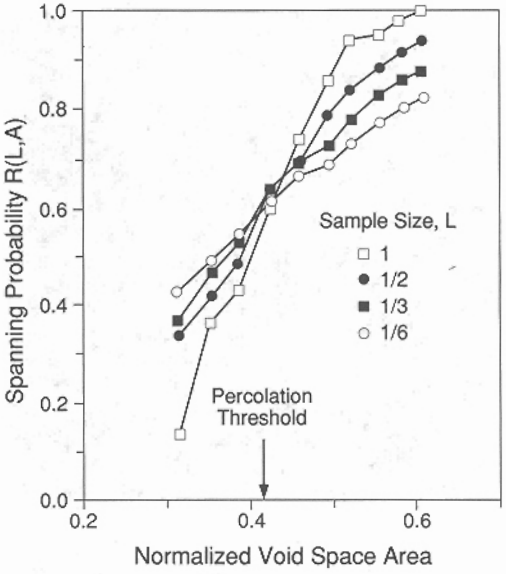

Fig. 3. Spanning probability of three-tier stratified percolation patterns calculated using renormalization group techniques for sample sizes of 1, 1/2, 1/3, and 1/6. The threshold occurs at A_c = 0.53. (Nolte, 1989). Area normalized with respect to flow path pattern area.

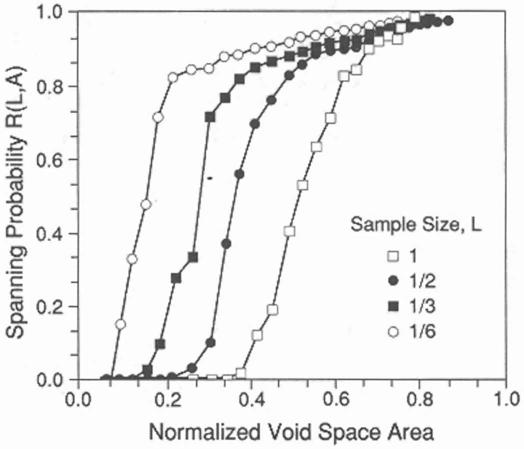

Fig. 4. The size of the spanning cluster (three-tier stratified percolation patterns for grid sizes 1, 1/2, 1/3, and 1/6) as a function of area fraction of void spaces. Area normalized with respect to flow path pattern area.

correlations that are naturally included in stratified percolation cause the clusters to clump together. Therefore when a spanning cluster occurs, it is likely that most of the void space will belong to that cluster. Also, the apparent percolation threshold moves to lower fractions of void space area as the sample size decreases. For our smallest size in the simulations, the apparent threshold is near $A = 0.15$.

The percolation probabilities described here can in principle be obtained experimentally from core samples by imaging the flow path geometries using the metal injection techniques of Pyrak-Nolte et al. (1987). Such a statistical study would establish whether a given fracture was above or below the percolation threshold. This information is of significant qualitative importance because macroscopic fractures in the field may not support flow (if the void geometry is below the percolation threshold) even if core samples do have connected paths across the samples.

The final difficulty is to find quantitative values for the flow. Unfortunately, there is no direct method means of determining flow rates from percolation probabilities though obvious trends exist; e.g., increased percolation probability will yield higher flow rate. The most important point is that fluid conductivity apparently decreases with increasing sample size, if all else remains the same. There is a simple size scaling relationship for systems near the percolation threshold which can be used to compare conductivities measured at different scales. The size dependence of the conductivity (Stauffer, 1985) is given by $k(L) \propto L^{-t/\nu}$ where t is the conductivity exponent (Halperin et al., 1985) and $\nu = 4/3$ is the correlation exponent.

UNSATURATED FLUID FLOW

Unsaturated fluid flow through single natural fractures was also analyzed using stratified continuum percolation. Unsaturated flow occurs when two or more phases are present in the fracture. We investigated the relative permeabilities of two immiscible fluids in a simulated fracture geometry and considered the effect of stress on relative permeability. This investigation does not deal with invasion percolation or trapping percolation. We allow the non-wetting phase to occupy the large voids and assume steady-state conditions when we calculate relative permeabilities. The results from this unsaturated fluid flow investigation are based on ten simulations of fracture flow path geometry, all of which used a five tier model with twelve points per tier and a scale factor of 2.37. A representative pattern is shown in Figure 2.

Analysis of unsaturated flow through a simulated fracture begins by saturating the void space with wetting phase. The non-wetting phase is introduced into the largest apertures and then allowed to occupy progressively smaller apertures. The phases are assumed to have the same density and viscosity, but different surface tensions. As the non-wetting phase is allowed into smaller apertures, it eventually forms a connected path of highest apertures, and begins to flow (Fig. 5a). Both the wetting phase and the non-wetting phase then flow through the fracture. If the non-wetting phase is allowed into even smaller apertures, it will eventually cut-off the percolating path of the wetting phase which then ceases to flow (Fig. 5b).

The first critical neck for the wetting phase, which is also the minimum aperture along the connected path of highest apertures, is operable until it is occupied by non-wetting phase which then begins to flow. When the non-wetting phase begins to flow, this phase will always flow along the critical path because the non-wetting phase has been introduced into the largest apertures. The final critical neck for the wetting phase is the critical connection that maintains a percolating path for the wetting phase. It operates until filled with non-wetting phase, causing the wetting phase to cease to flow.

In order to determine the relative permeabilities of the two phases in a fracture, relative flow of each phase was evaluated. To calculate fluid flow through the model, a zeroth order approach is taken that includes only the simplest dependences, which are: (1) the cubic law describes the local dependence of fluid flow on aperture; and (2) the two-dimensional critical behavior is included by a scaling law that describes changing tortuosity. Laminar, flow between parallel plates (cubic law) is assumed for fluid flow of both phases through the critical neck. Tortuosity is important only for calculating the wetting phase permeability because as the non-wetting phase is introduced, the wetting phase is robbed of its high aperture path or critical path, and its path becomes more tortuous as it retreats.

The expression for wetting phase flow through the pattern is

$$Q_w \propto \left\{ b_{wc1}^3 \left[a_w - a_{wc1} \right]^{1.9} \right\} + \left\{ b_{wc2}^3 \left[a_w - a_{wc2} \right]^{1.9} \right\} \quad (1)$$

where

w - wetting phase

c - critical

Q - flow

a - area normalized with respect to whole area of the fracture

b - aperture of critical neck

1 or 2 - first or final critical neck

Tortuosity is incorporated into the expression for relative permeability of the wetting phase (Eq. (1)) through a scaling term, $(a_w - a_{wc1})^t$, where a is the normalized area occupied by the wetting phase, a_c is the normalized area of the wetting phase at percolation threshold, and the exponent t is a critical exponent. The critical exponent, t, can range between 1.7 and 2.7 for standard random continuum percolation. We have assumed a value of 1.9 for the critical exponent.

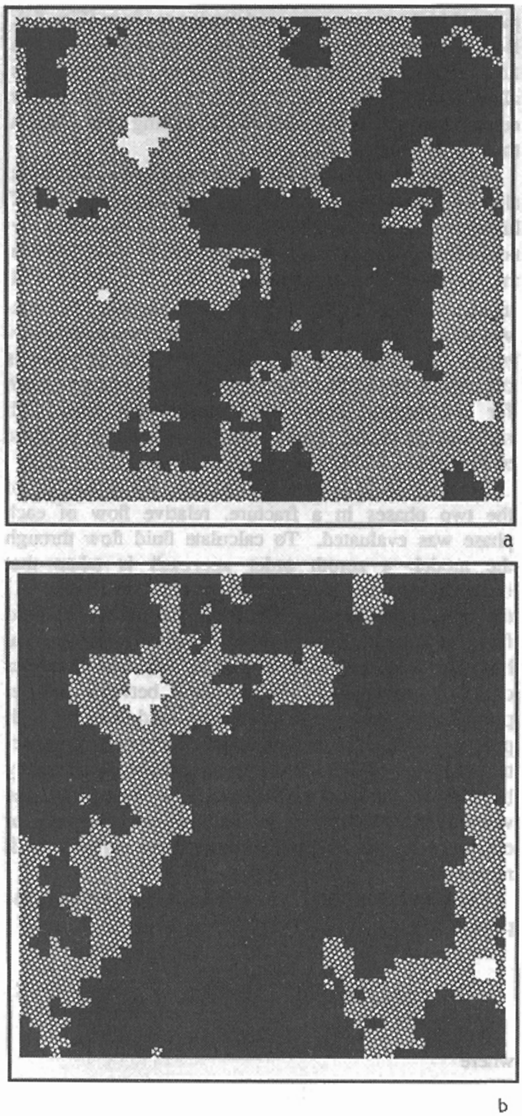

Fig. 5. Depiction of area of void spaces occupied by wetting phase (gray), and non-wetting phase (black), and contact area (white) for non-wetting phase in apertures larger than (a) 89 units of aperture, and (b) 30 units of aperture.

The non-wetting phase flow, in contrast, is always dominated by the main critical path because it occupies the largest apertures of the pattern. Therefore, the tortuosity of the non-wetting phase does not change with increasing non-wetting phase saturation. However, the width of the non-wetting phase flow path does change with increased non-wetting phase saturation and must be accounted for in the relative flow expression. The expression for non-wetting phase flow is

$$Q_{nw} \propto b^3_{nwc1} [a_{nw} - a_{nwc1}] . \qquad (2)$$

where nw means non-wetting. The expression for the non-wetting phase flow is simply a cubic dependence on aperture and a linear dependence on the change in area occupied by the non-wetting phase.

Assuming that the densities and viscosities of the two phases are the same, relative permeabilities for the two phases were calculated and plotted as a function of wetting phase saturation as shown in Figure 6. A rapid decrease in non-wetting phase permeability is observed with an increase in wetting phase saturation. The cross-over in permeabilities, where the permeability of both phases is equal, occurs at a wetting phase saturation of around 32 percent. The non-wetting phase ceases to flow around forty-five percent wetting phase saturation.

The effect of stress on relative permeabilities of fluids in a fracture was evaluated by applying stress to the generated patterns of fracture geometry and analyzing the relative flows. Application of stress is viewed as a reduction of all the apertures, an increase in the contact area, and a reduction in void volume. We investigated the effects of stress for three stresses which are referred to by the amount of aperture closure (5, 20, 50). A closure of 50 units of aperture is about a third of the largest apertures in the pattern. The overall effect of stress is to reduce the relative permeabilities (Fig. 7a). To illustrate the effects of stress, the relative permeabilities under stress have not been normalized to unity but are shown relative to unit normalized permeability at zero stress. The rapid decrease in non-wetting phase saturation is still observed. In addition, it is seen in Figure 7b that the cross-over point is essentially invariant with respect to stress. For all stresses the crossover occurs between 26-32 percent

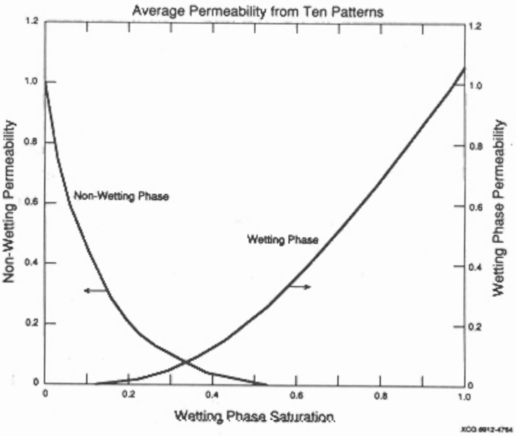

Fig. 6. Relative permeability of the non-wetting phase and wetting phase as a function of wetting phase saturation.

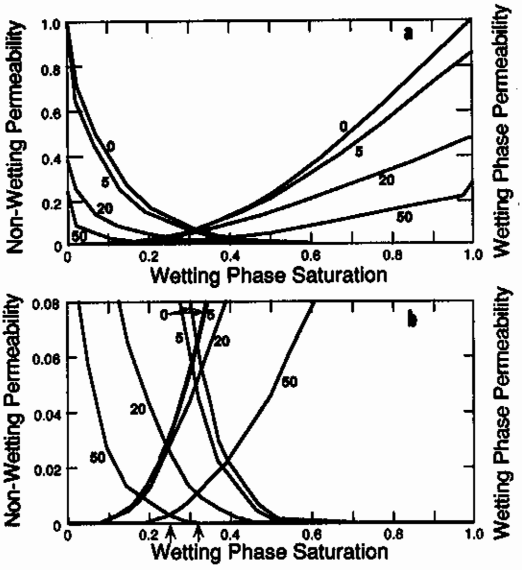

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Fig. 7. Effect of stress (a) on relative permeability for a reduction in aperture of 5, 20, and 50 units, (b) An enlargement of the cross-over region of (a), the arrows indicate the minimum and maximum value of wetting phase saturation for the cross-overs in relative permeabilities as a function of stress. The cross-overs in relative permeability are essentially invariant of stress.

wetting phase saturation. This leads to the important conclusion that if the percentage saturation of one of the phases is known, one can determine which phase dominates the flow at any stress.

CONCLUSIONS

A stratified continuum percolation model was used to simulate experimentally-observed flow path geometries. This model, which is based on a fractal construction, yields correlated contact area distributions and aperture distributions. A percolation model was chosen in order to use the existing body of knowledge of percolation theory to analyze fluid flow through single fractures. Using the results of percolation theory and the principle of conservation of volume, we were able to understand the deviations from cubic law behavior that have been observed for saturated fluid flow through single fractures. Also, we were able to analyze unsaturated fluid flow through single fractures using the stratified percolation model.

A major issue in experimental work concerns the relationship between behavior measured on small laboratory samples (less than a meter in dimension) and fluid flow through fractures in the field (with dimensions perhaps of kilometers). Using renormalization group theory, we have begun to address this issue of the effect of sample size on the hydraulic properties of single fractures. Renormalization group theory deals specifically with the question of how the physical properties of random patterns scale with the size of observation. From this analysis, it was found that the probability that a fracture will support fluid flow is dependent on sample size.

ACKNOWLEDGEMENTS

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During the last few decades considerable interest has developed in the possibility of storing gas in rock caverns. Today rock caverns are used for storage of a wide variety of gases, including hydrocarbons, air, hydrogen & ammonia. The possibility of storing natural gas in rock caverns is currently being evaluated in several countries. Compared to the concept of gas storage in surface tanks, safety, environmental & economical factors are considered to represent major advantages of the concept of sub-surface storage. Storage in rock caverns, however, may also involve problems. Safety hazards & considerable extra costs due to unexpected leakage have, in some cases, been experienced. Discussions on the various rock mechanical & hydrodynamical aspects of storage of gases in rock caverns. Mined caverns in hard & soft rock as well as solution cavities in salt are included. 42 papers. Editors: Norwegian Inst. Technology, Trondheim & Saga Petroleum a.s., Hovik.

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Proceedings: 6th congress of the International Society for Rock Mechanics/ Comptes-rendus: 6ème congrès de la Société Internationale de Mécanique des Roches / Berichte: 6er Kongress der Internationalen Gesellschaft für Felsmechanik, *Montreal, Canada, 1987*
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