Title
MECHANICAL and HYDRAULIC PROPERTIES OF ROCKS RELATED TO INDUCED SEISMICITY

Author
Wither Spoon, Paul A.

Publication Date
1976

Presented at First International Symposium on
Induced Seismicity, Banff, Alberta, Canada,
September 15-19, 1975; To be published in
special issue of Engineering Geology

LBL-4455
c.1

MECHANICAL AND HYDRAULIC PROPERTIES OF ROCKS RELATED TO INDUCED SEISMICITY

Paul A. Witherspoon and John E. Gale

January 1976

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA • BERKELEY •

DISCLAIMER

MECHANICAL AND HYDRAULIC PROPERTIES OF ROCKS RELATED TO INDUCED SEISMICITY

by

Paul A. Witherspoon, Lawrence Berkeley Laboratory and
Department of Civil Engineering, University of California, Berkeley

John E. Gale, Department of Civil Engineering,
University of California, Berkeley*

ABSTRACT

The mechanical and hydraulic properties of fractured rocks are considered with regard to the role they play in induced seismicity. In many cases, the mechanical properties of fractures determine the stability of a rock mass. The problems of sampling and testing these rock discontinuities and interpreting their non-linear behavior are reviewed. Stick slip has been proposed as the failure mechanism in earthquake events. Because of the complex interactions that are inherent in the mechanical behavior of fractured rocks, there seems to be no simple way to combine the deformation characteristics of several sets of fractures when there are significant perturbations of existing conditions. Thus, the more important fractures must be treated as individual components in the rock mass.

In considering the hydraulic properties, it has been customary to treat a fracture as a parallel-plate conduit and a number of mathematical models of fracture systems have adopted this approach. Non-steady flow in fractured systems has usually been based on a two-porosity model,

---

*Now with Geological Survey of Canada, Ottawa.

which assumes the primary (intergranular) porosity contributes only to storage and the secondary (fracture) porosity contributes only to the overall conductivity. Using such a model, it has been found that the time required to achieve quasi-steady state flow in a fractured reservoir is one or two orders of magnitude greater than it is in a homogeneous system. In essentially all of this work, the assumption has generally been made that the fractures are rigid.

However, it is clear from a review of the mechanical and hydraulic properties that not only are fractures easily deformed but they constitute the main flow paths in many rock masses. This means that one must consider the interaction of mechanical and hydraulic effects. A considerable amount of laboratory and field data is now available that clearly demonstrates this stress-flow behavior. Two approaches have been used in attempting to numerically model such behavior: (1) continuum models and (2) discrete models. The continuum approach only needs information as to average values of fracture spacing and material properties. But because of the inherent complexity of fractured rock masses and the corresponding decrease in symmetry, it is difficult to develop an equivalent continuum that will simulate the behavior of the entire system. The discrete approach, on the other hand, requires details of the fracture geometry and material properties of both fractures and rock matrix. The difficulty in obtaining such information has been considered a serious limitation of discrete models, but improved borehole techniques can enable one to obtain the necessary data, at least in shallow systems. The possibility of extending these methods to deeper fracture systems needs more investigation. Such data must be considered when deciding whether to use a continuum or discrete model to represent the interaction of rock and fluid forces in a fractured rock system, especially with regard to the problem of induced seismicity. When one is attempting to alter the pressure distribution in a fault zone by injection or withdrawal of fluids, the extent to which this can be achieved will be controlled in large measure by the behavior of the fractures that communicate with the borehole. Since this is essentially a point phenomena, i.e. the changes will propagate from a relatively small region around the borehole, the use of a discrete model would appear to be preferable.

INTRODUCTION

In considering the mechanical and hydraulic properties of rocks in relation to the concept of induced seismicity, one immediately must recognize that rock masses consist of at least two sub-domains: (1) the intact rock blocks and (2) the discontinuities. In this review, we will usually refer to these discontinuities as fractures, although this term could also mean faults, joints, fissures, etc. It is generally recognized by workers in the field of rock mechanics that the intact blocks and the fractures can have considerably different mechanical and hydraulic properties. In many cases the mechanical properties of fractures determine the stability of a rock mass (Jaeger, 1971). The presence of fractures on outcrops and in deep mines indicates that fractures are a pervasive feature of the earth's crust although their mechanical and hydraulic properties vary considerably with depth and rock type (Brace, 1974; Bishop, 1974).

In the United States where seismicity has been detected as a result of human activities at the Rocky Mountain Arsenal well near Denver (Lane, 1969) and in the Rangely oil field in western Colorado (Raleigh et al., 1972), the changes in stress due to porewater pressure variations were only a small fraction of the compressive strength of the rock. In addition, the stress changes were basically changes in effective stress not total stress. Thus, it has been suggested that the movements producing the seismic activity occurred not through the breakage of intact rock but along pre-existing fault or fracture planes (Lane, 1969; Raleigh et al., 1972). There may also be breakage along planes of weakness that consist of a combination of fracture planes and the intervening rock bridges (Lajtai, 1975).

In this review, it is assumed that existing fractures are the paths along which failure occurs in regions of induced seismicity. Therefore, the mechanical and hydraulic properties of fractures will be presented rather than the properties of the intact rock blocks themselves. For a discussion of the behavior of intact rock under failure conditions, the reader is referred to Brace et al. (1966); Bieniawski (1968); and Jaeger and Cook (1969).

While intact rocks have been investigated in some detail, the mechanical and hydraulic properties of fractures have only recently been the subject of detailed investigations. It is impossible, within the scope of this review paper, to summarize the many attempts, both theoretical and experimental, that have been made to characterize the mechanical behaviour of fractures and fracture systems. Hence, the major papers describing work on the mechanical properties of fractures have been reviewed. The selection of these papers represents our own bias and the prominence of the material in the published literature.

MECHANICAL PROPERTIES OF FRACTURES

Sampling

Although it is relatively easy to obtain samples of intact rock, it is very difficult to obtain undisturbed samples of rocks containing natural fractures for laboratory testing purposes. Goodman (1974) describes the different methods used to obtain samples of natural fractures. These methods consist of (1) prebolting and overcoring perpendicular to the fracture plane, and (2) cutting a block of fractured rock either with a wire saw or by connecting boreholes, cementing the rock block together, and cutting appropriate samples with a diamond saw after the sample has been transported to the laboratory. In addition, relatively good samples of fractures can be obtained by drilling parallel to the fracture plane (Goodman, 1970). Drilling at an angle to the fracture plane can produce reasonably good samples if enough care is exercised in the drilling operations.

Because of the difficulty in obtaining samples containing natural fractures, many workers use artificially created fractures obtained by either splitting or sawing a rock block. The rough tension fractures obtained by splitting are representative of the surface roughness of some natural fractures. The saw-cut surfaces represent a somewhat idealized fracture surface but are useful in studies that attempt to separate the frictional properties of the rock from the added strength and complexity afforded by the interlocking asperities on rough surfaces (Coulson, 1970).

Thus, only fractures at or near the surface have been sampled and tested. At the depths at which most induced seismicity has been detected, very little is known about the character of the fracture surface but it is logical to assume that the mechanical character of such fractures lies between that measured on fresh unweathered artificial fractures and the highly weathered fractures obtained at outcrops. The presence of gouge in the fracture is an additional factor to be considered (Goodman, 1970; Ohnishi, 1973). Patton (1966) and Barton (1971) have used artificially created surfaces of plaster, etc. to study the effect of surface roughness on shear strength. The different frictional characteristics of such materials may make it difficult to compare the test results to those obtained from tests on rock surfaces (Jaeger, 1971). Barton (personal communication, 1975) avoids this criticism by recognizing that while the physical properties of his model material are related to the physical properties of rocks by one parameter, the stresses developed in the model are related to the stresses in the rock mass by a different parameter. Jaeger (1971) has given an excellent review of the different types of natural and artificial materials that have been used in studies of fracture surfaces.

Testing Methods

Jaeger (1971) reviewed the different methods that have been used to study the sliding of rock surfaces. The tests most applicable to studies of fracture characteristics (Figure 1) are: (a) triaxial tests (Jaeger, 1959) where a cylindrical samples with a joint or sawcut is inclined at a suitable angle to the cylinder axis, (b) direct shear tests (Krsmanovic, 1967; Locher, 1968; Hoek and Pentz, 1969; Goodman and Ohnishi, 1973) where either a constant normal stress or a constant normal displacement is maintained while the shear stress is increased to produce shear displacement along a pre-existing fracture, and (c) insitu shear tests (Rocha, 1964; Zeinkiewicz and Stagg, 1966; Pratt et al., 1974a; Franklin et al., 1974).

Each test has certain advantages and disadvantages. The results of triaxial tests are dependent on the sample ends being free from horizontal constraints. As shear displacement occurs there is a continuous decrease in contact area and this must be taken into account (Rosengren, 1968). Both the normal and tangential displacements can be obtained indirectly by measuring axial and lateral displacements and rock strains during the test and then performing the necessary calculations. The direct shear test gives both normal and shear displacements

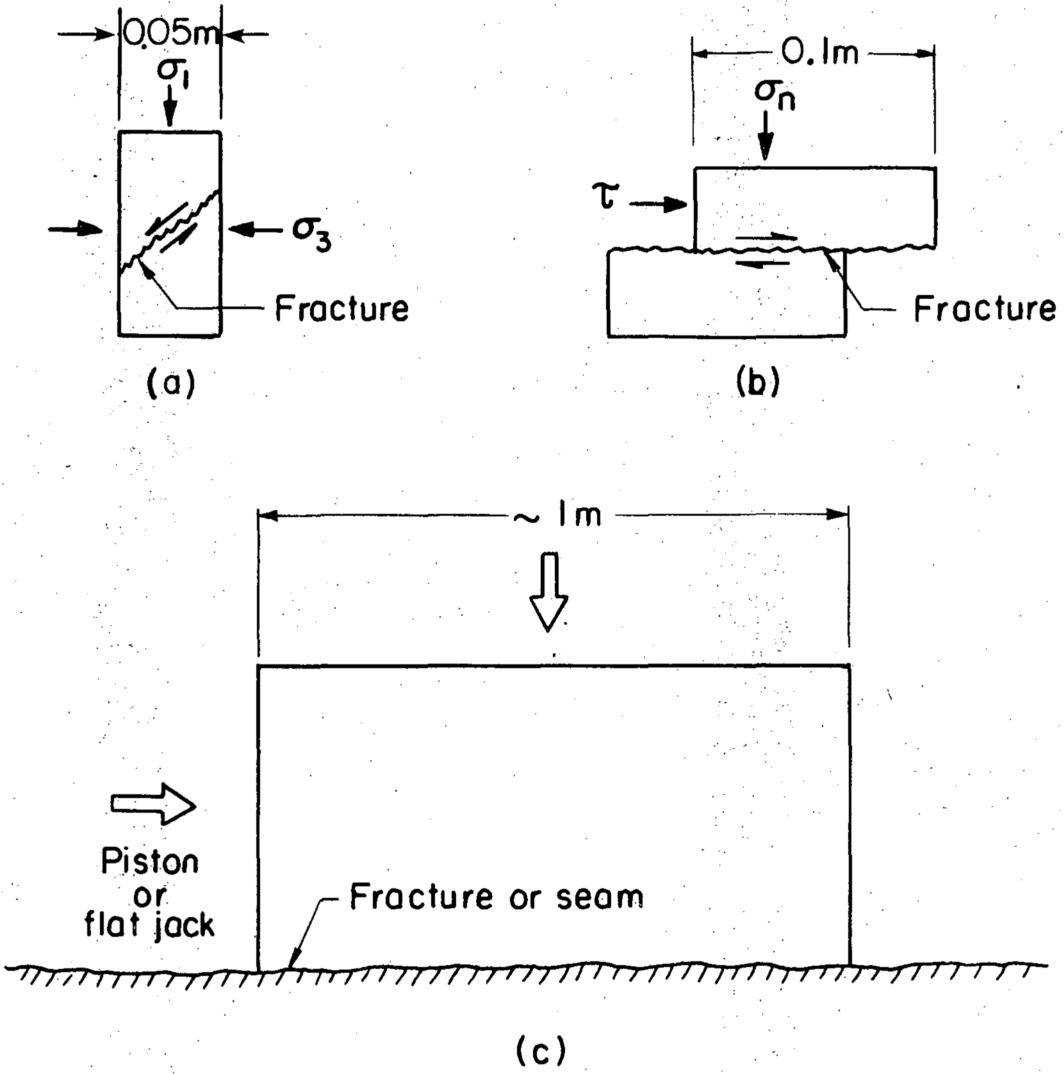

Fig. 1. Schematic of fracture testing methods: (a) triaxial, (b) direct shear, (c) insitu shear.

directly as well as the relationship between normal and shear stress. Most researchers have maintained approximately a constant normal load during direct shear tests but this will lead to a low estimate of shear strength in situations where plane strain boundary conditions exist (such boundary conditions should exist in areas of slip along vertical or near vertical boundaries). In such cases it would be more appropriate to use a constant normal displacement condition, as suggested by Locher (1968).

Insitu shear tests have the advantage of a large sample area and direct testing of the fracture. One disadvantage is the high cost, and because of the loading mechanism there is some question about the uniformity of stress distribution within the fracture plane. Pratt et al. (1972) have used specially constructed flatjacks to control boundary conditions in a field study of artificial fracture surfaces. More recently, Pratt et al. (1974b) used the same system to study the insitu response of a large block (3 m x 3 m x 3 m)[1] of naturally fractured granitic rock under both uniaxial and biaxial loading conditions.

The scale of the fracture specimens tested will depend on the availability of equipment and costs. But, as shown by Bernaix (1969) and Pratt et al. (1974b), the best approach is one in which samples of the rock mass are tested both insitu and in the laboratory.

---

[1] The following conversions to the metric system may be useful:

Length: 1 m = 3.281 ft = 39.37 in.

Pressure: 1 kg/cm^2 = 0.9678 atm = 0.9807 bars = 14.22 psi
= 9.807 x 10^4 n/m^2.

Results of Tests on Fractures

The results of laboratory tests are generally reported in terms of fracture stiffness - force per unit displacement (Goodman et al., 1968). Generalized curves for the normal and shear stiffness of a fracture are given in Figures 2 and 3. From Figure 2 it can be seen that a straight line approximation to the normal displacement curve results in a normal stiffness value K_N that is highly dependent on the existing state of stress.

The normal force-normal displacement curve on Figure 2 has been described as being semi-logarthmic (Shehata, 1971) and closely approximated by a hyperbola (Goodman, 1974). Snow (1972) suggests such nonlinear curves may be appropriate for "virgin" fractures that have not closed before. Snow refers to unpublished data by Shehata that indicates essentially linear deformability with repeated loading below some previously attained maximum load. Gale (1975) found that even with stiff saw-cut fractures in a large (~1 m) diameter granite core the nonlinearity persisted with repeated loading (Figure 4).

Undoubtedly, the nonlinearity of the normal force-displacement curve is related to the percentage of the two fracture surfaces that are intially in contact. As a rule, fractures once open will not fit perfectly back together again and will thus exhibit some degree of nonlinear normal force-displacement behavior. Stress-strain data from a large field test (Pratt et al., 1974b) shows the relative contribution to the total displacement field of the fractures, microcracks and the intact rock (Figure 5) as well as the nonlinear nature of the normal force-displacement curve.

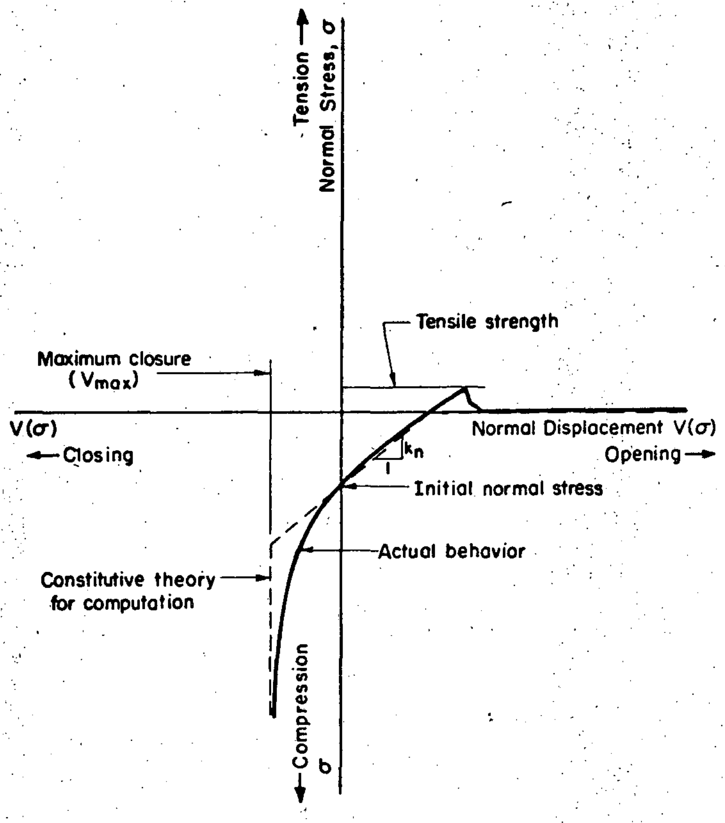

Fig. 2. Constitutive model for the displacement of a fracture under normal stress (after Goodman and Dubois, 1972).

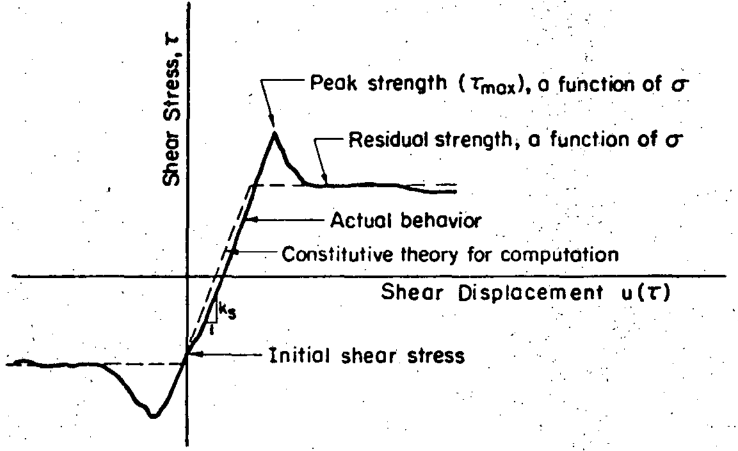

Fig. 3. Constitutive model for the displacement of a fracture under shear stress (after Goodman and Dubois, 1972).

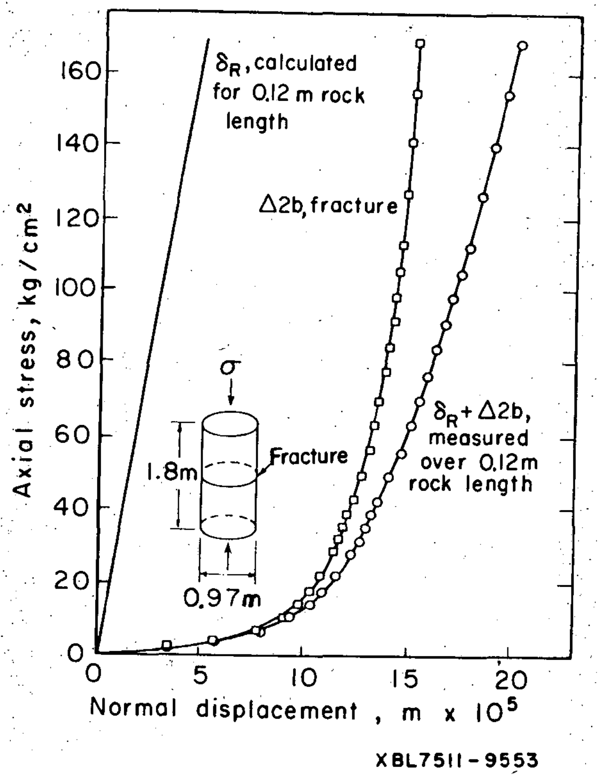

Fig. 4. Deformation of 0.97 m x 1.8 m granite cylinder with saw-cut fracture (after Gale, 1975).

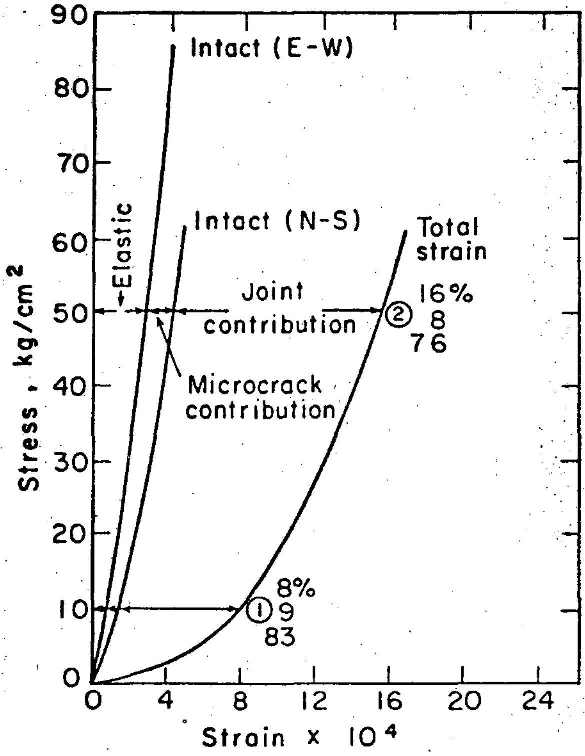

Fig. 5. Comparative stress-strain curves showing relative contributions of elastic, microcrack, and joint deformations (after Pratt et al., 1974b).

The shear force-shear displacement curve (Figure 3), based on a constant normal stress, consists of three parts: (1) an initial linear section with a shear stiffness K_S reaching, (2) a peak shear strength followed by, (3) a residual shear strength condition. As shown by Jaeger (1971) the shear stiffness K_S of specimens with fresh ground surfaces is independent of the normal stress (Figure 6a) but tests on the same material with rough worn surfaces showed that in such cases the shear stiffness apparently depends on the normal stress (Figure 6b).

As indicated in Figures 3 and 6 the peak shear strength and the residual shear strength are dependent on the magnitude of the applied normal force. Based on a review of shear strength data and his own experimental work on fractures, Barton (1974) states that while peak shear strength is largely dependent on the effective normal stress acting across the fracture, it is also sensitive to the degree of surface roughness, compressive strength of the rock, degree of weathering, mineralogy, and presence or absence of water. Also, the ratio of the peak shear strength to residual shear strength is dependent on the magnitude of the normal load, the size of the asperities in the fracture plane, the ratio of static to dynamic friction, presence or absence of filling material, and the nature of the boundary conditions (constant normal force or constant normal displacement).

As pointed out by Goodman (1974), the residual strength of rough clean fractures gradually approaches the peak shear strength of the fracture with increasing normal load. For filled fractures the stress-deformation curve resembles that of clay with a poorly defined peak and continuous curvature. At constant normal load, Jaeger (1971) reports the peak shear strength approaches the residual shear strength with

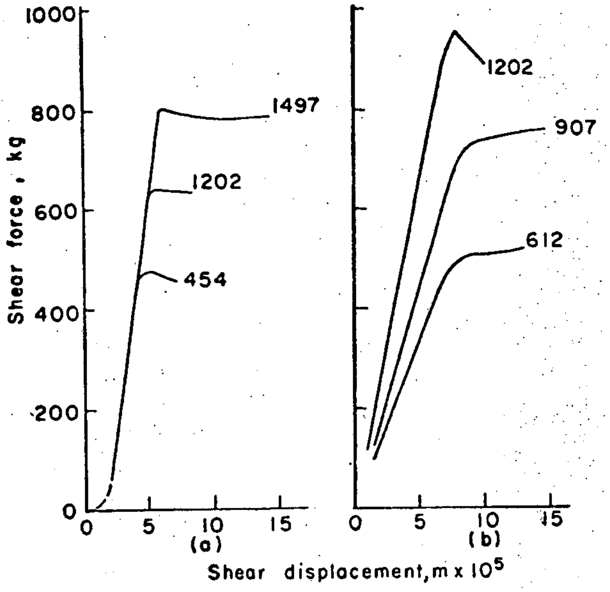

Fig. 6. Load-displacement curves for ground Bowral trachyte showing: (a) early part on 0.0058 m^2 specimen, and (b) early part on 0.0033 m^2 specimen with worn surfaces. Numbers show normal loads in kg (after Jaeger, 1971).

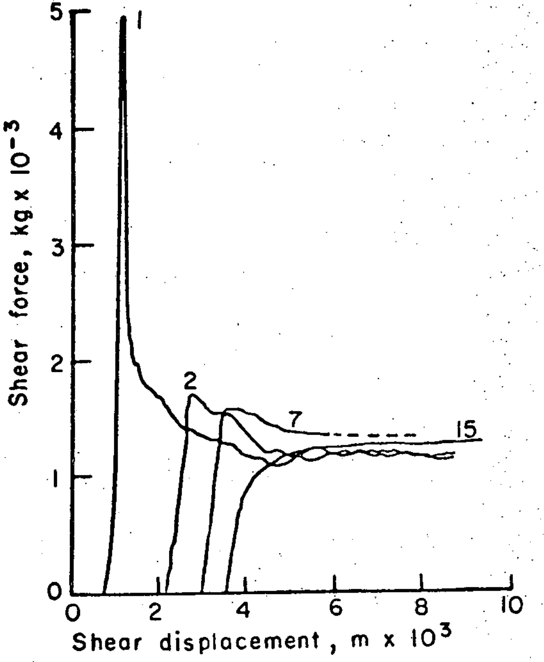

Fig. 7. Variation of frictional force with displacement for a tensile fracture in Bowral trachyte; area 0.0033^2; normal load 612.3 kg (after Jaeger, 1971).

increased wear of the fracture surface as shown in Figure 7. The fracture surfaces were cleaned and remated after 0.01 m of displacement and then the shear test repeated. The numbers on the curves refer to the sequential order of the test.

Figure 8 demonstrates the effect of either a constant normal stress or a constant normal displacement boundary condition on the character of the shear-deformation curve. The change in normal displacement and normal stress in Figures 8a and 8b indicates the dilatant nature of natural fractures. The dilatancy of natural fractures is dependent on the magnitude of the normal stress. Goodman and Dubois (1972) have shown that at low normal stresses fractures open (dilate) during shear displacement but close (contract) under high normal stresses. Ohnishi and Goodman (1974) found that rough fractures in samples of granite, rhyolite and friable sandstone dilate significantly during shear when the normal stress was less than 20 percent of the unconfined compression strength of the intact rock. Dilatancy is a result of the roughness of the fracture wall but rotation can also be a contributing factor (Goodman, 1974) at least in the failure of rock slopes.

Rengers (1970) in summarizing the work of Patton (1966) has prepared Figure 9 to demonstrate the influence of surface roughess on the effective angle of friction and hence on the shear strength of the fracture. As shown in Figure 9 the effective friction angle at low normal stresses includes both the friction of the smooth surfaces (line 1) and the effects of the asperities (line 2). When the normal stress is increased to the point where shearing occurs through the asperities, the normal stress-shear stress relationship is governed by an angle of internal

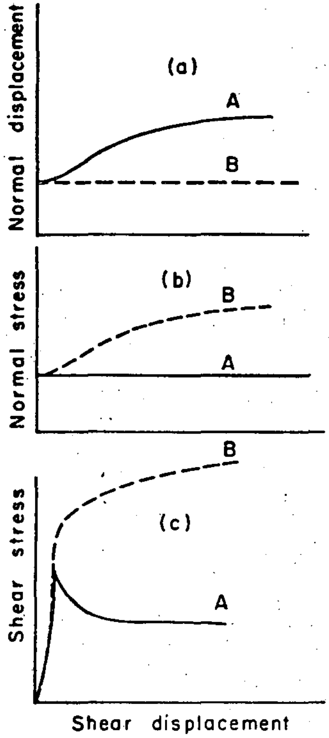

Fig. 8. Effect of test mode on shear deformation of dilatant joint under: A - constant normal pressure, B - restricted normal displacement (after Goodman, 1974).

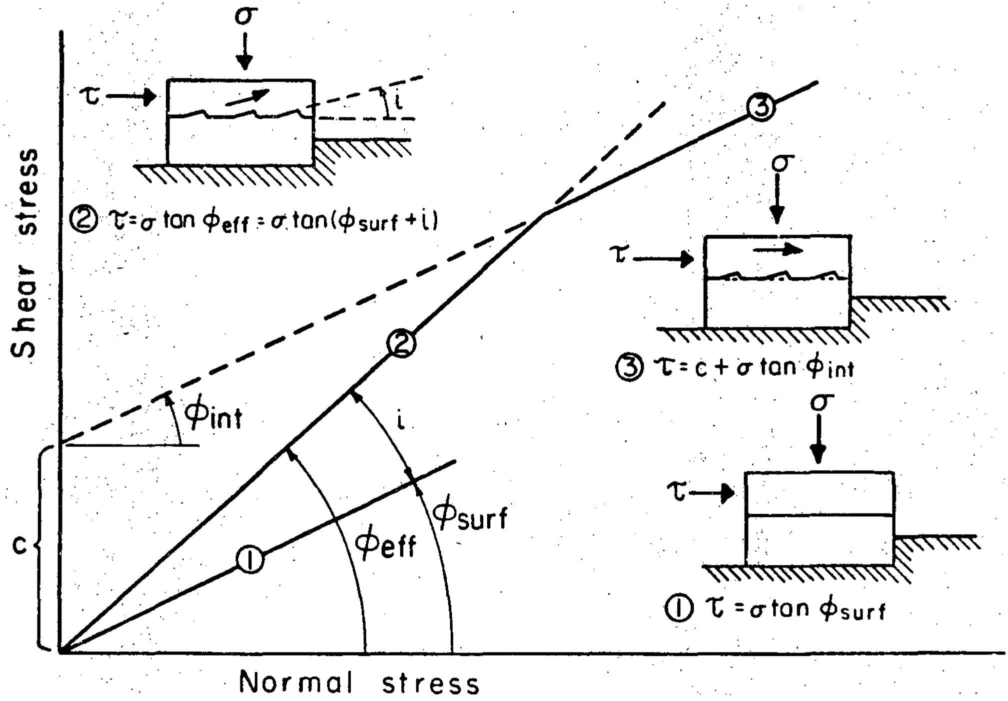

Fig. 9. Influence of surface roughness on angle of friction (after Rengers, 1970).

friction (line 3). Thus, Patton proposed a bilinear constitutive model whereas the constitutive relationships of Ladanyi and Archambault (1970) and Barton (1973, 1974) resulted in non-linear stress-strain envelopes. The bilinear model may be accurate enough for most situations, but the constitutive model proposed by Barton (1973) permits one to predict the peak shear strength from measured parameters and to extrapolate shear strength values from a limited number of tests. The use of the bilinear model suggests a cohesion factor (C in Figure 9) whereas the use of a cohesion intercept at low or zero normal stress would be inadmissible with a non-linear model (Barton, 1973). This observation is consistent with the no-tension-strength characteristics of most fractures.

Failure Mechanisms

Some researchers (Byerlee, 1967; Byerlee and Brace, 1968, Dieterich, 1972; among others) believe that the unstable sliding which occurs at high normal stresses due to shearing through the asperities is a possible earthquake mechanism. This unstable sliding, referred to as "stick-slip" in the literature, has been described by Jaeger (1971) using a simple mechanical model (Figure 10). Jaeger assumes that the coefficient of dynamic friction μ' is constant and less than that of static friction μ. A normal force W is applied to a mass M. A spring of constant k is attached to the mass M with its free end moving at a constant velocity, v. When the energy stored in the spring is sufficient to overcome the force of static friction,the mass M will slip. When slip occurs the frictional force is controlled by the dynamic coefficient of friction and hence the mass M will slip at a much greater velocity than the velocity v of the free end of spring. With sufficient displacement of the mass M in the direction of the spring movement, the energy stored in the spring will be decreased below that required to maintain slip. The mass M will stop, static friction will become effective and the process will be repeated. This intermittent type of slip with the associated oscillation of forces in the system has been observed in experiments on unfractured granite with saw-cut surfaces (Nur, 1974).

It is obvious from the examples of the fracture tests discussed here that fractures respond in many complex and nonlinear patterns to changing loading conditions. Some authors have attempted to use the characteristics of the fracture system to construct equivalent continuum models (Goodman and Duncan, 1971). This approach has been used by Riney et al. (1973) to construct computer models for ground motion predictions. It is interesting to note that Goodman (1974) states that an "equivalent orthotropic medium cannot be constructed to fairly represent the deformability of regularly jointed rock" because: (1) the normal deformation of the fractures is heavily stress dependent, (2) the dilatancy and mode of shear deformation depend on the sign of the shear stress as well as the magnitude of the normal stress, (3) dilatancy reduces the elastic symmetry to a class lower than orthotropic. Also, Goodman states that there seems to be no simple way to combine the deformation characteristics of several sets of fractures and thus the more important fractures must be treated as individual components in the rock mass.

HYDRAULIC PROPERTIES OF FRACTURES

In attempting to treat the problem of fluid flow in fractured rocks, it has been customary to assume that a natural fracture can be represented by a parallel plate opening as shown in Figure 11. Romm (1966) has shown how an expression for laminar flow in such an idealized model of a single fracture can be derived from the Navier-Stokes equations. He obtains the well known relationship between flow rate q and pressure gradient dp/dx

$$q = \frac{(2b)^3}{12\mu} \frac{dp}{dx} \qquad (1)$$

where 2b is the size of the fracture aperture and μ is the fluid viscosity. Since the cross-sectional area for flow is $2b \cdot 1$, the average velocity v is simply

$$v = \frac{(2b)^2}{12\mu} \frac{dp}{dx} \qquad (2)$$

We see that flow in a fracture is a sensitive function of aperture size. The validity of these equations extends only through the region of laminar flow, but it seems that this type of flow is dominant in most field situations (Ollos, 1963; Louis, 1969).

A great many workers have analyzed flow in fractured rocks using equations 1 and 2. Wilson and Witherspoon (1970) have made a review of investigations on this subject and include an extensive set of references. Snow (1965) has presented a thorough review of fracturing based on existing geological literature. Hodgson (1961a,b) has provided a basic framework for describing fractures in the field. Snow (1965), Kiraly (1969), and Mahtab et al. (1973) have contributed to the statistical description of fracture orientations. Parsons (1972)

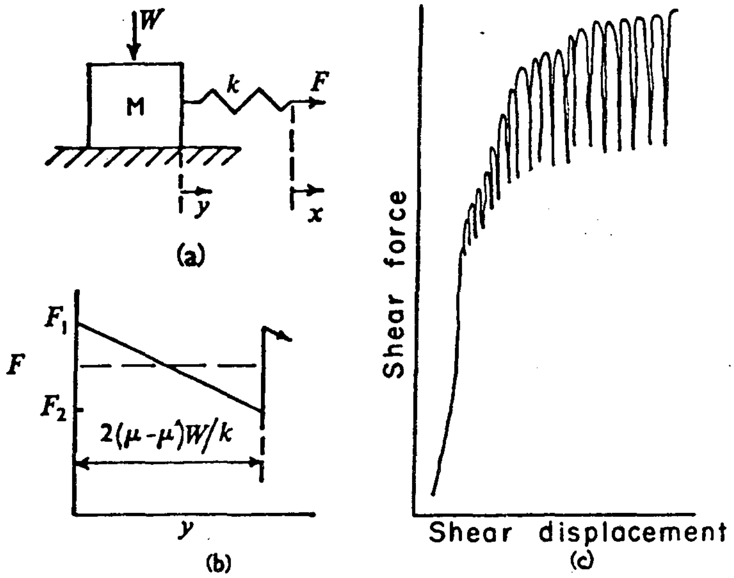

Fig. 10. Stick-slip: (a) and (b) simple mechanical model, (c) detail of regular stick-slip on smooth granite (after Jaeger, 1971).

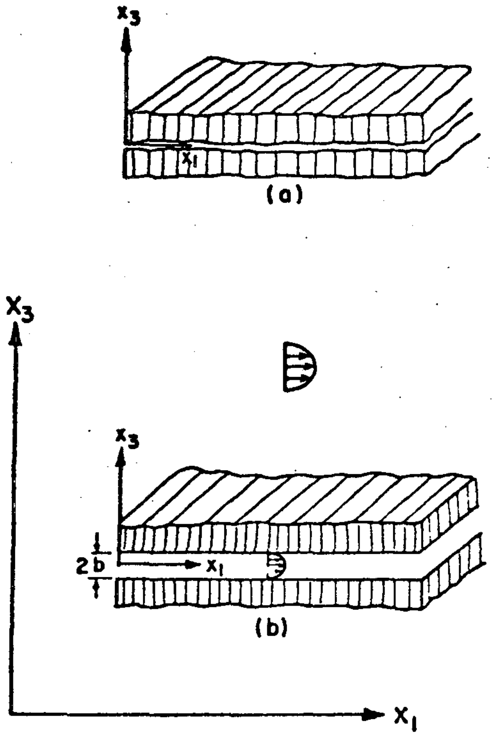

Fig. 11. Flow in a rock discontinuity: (a) natural fracture, (b) parallel plate opening.

used Snow's and Kiraly's approach in a study of the contribution of flow in fractures to regional groundwater systems.

Laboratory and Field Work on Fracture Flow

One of the earliest and most extensive laboratory experiments on fluid flow in fractures was conducted by Lomize (1951). He modeled a fracture using two thin glass plates with variable cross-sections and curvilinear shapes. Lomize examined the transition zone between laminar and turbulant flow and also investigated the effect of fracture roughness. Louis (1969) extended the work of Lomize in a series of laboratory experiments on single fractures and has presented a series of flow laws to account for different degrees of fracture roughness.

From results of laboratory tests on a single natural fracture in porphyry, Sharp (1970) questions the applicability of equation 1 in describing laminar flow under his laboratory conditions. He concluded that the fracture discharge was related to the aperture by some exponential factor less than three. However, a review of his data reveals that there was still a measurable discharge for the "closed" position of his fracture. This suggests that Sharp did not have an accurate measure of the effective aperture. In dealing with a natural fracture, there is also the problem of the effect of roughness (Lomize, 1951). It would appear therefore that Sharp's conclusion as to the inapplicability of equation 1 is not justified on the basis of these limited experimental results.

Maini (1971) used a transparent modelling material to duplicate a natural fracture. By injecting dyes into the discontinuity, Maini was able to clearly demonstrate the discontinuous nature of the flow field within the fracture plane when the fracture surfaces were in contact. Maini also discussed different methods of collecting and interpreting field data when studying the hydraulics of fractured media.

The fundamental characteristics of flow in natural fractures is the subject of an ongoing research project at the University of California. One of the items of interest is the manner in which the permeability decreases as a fracture closes. Iwai (personal communication, 1975) is investigating this problem using numerical and laboratory models. An example of his numerical results for the pressure distribution with radial flow in a horizontal fracture where only 15 percent of the flow paths are blocked is shown in Figure 12. In this case, the impermeable contact area caused a reduction in flow of approximately 35 percent. Iwai (personal communication, 1975) has found that when 50 to 60 percent of the flow paths are blocked at random, the permeability of a radial flow system such as this has almost vanished. Obviously, once the sides of a fracture begin to touch at the protruding points, the cross-section for flow can change significantly.

Banks (1972) has discussed the problem of making field measurements of fracture permeability. Borehole camera surveys and field mapping were used to calculate flow rates for comparison with injection tests in moderately jointed basalt. Banks states that when laminar flow prevailed, the calculated results were within an order of magnitude of the measured flow rates. In some situations, however, the results differed by as much as four orders which Banks attributed to the effects of turbulence. In commenting on these results, Snow (1972) has suggested that the assumption of turbulent flow is not a valid explanation for the observed discrepancies. Snow states that more precise information on fracture geometry is needed before one can predict permeability with confidence.

In the field of groundwater hydrology, various attempts have been made to develop methods of analyzing pump test results that could be applied to fractured aquifers. Hantush (1966) assumed that such aquifers could be represented by an equivalent anisotropic system and could be evaluated accordingly. A more practical method has been presented by Papadopoulos (1967) in which the anisotropy is assumed to result from joint patterns that cause permeability variations in different directions. The solution obtained by Papadopoulos enables one to determine the maximum and minimum permeability and the storage coefficient.

In the petroleum industry, there has been an extensive development of pressure buildup analysis in wells because of the wide use of hydraulic fracturing to stimulate production. One of the early methods of analyzing such data has been developed by Ramey (1970) and relies on type curve matching techniques. More recently, analytical solutions have been developed to describe the behavior of a well that intersects a single horizontal fracture (Gringarten and Ramey 1974) or a single vertical fracture (Gringarten, et al., 1974). Gringarten and Witherspoon (1972) have developed methods of analyzing the pressure behavior in either the pumping well or a nearby observation well using a series of type curves. With the aid of these curves, it is possible to distinguish between aquifers with horizontal and vertical fractures, and to analyze the system as an "equivalent" anisotropic homogeneous porous medium with a single fracture of much higher permeability.

Mathematical Models of Fracture Flow

Mathematical modelling of fluid flow in fractured rock masses has taken two directions: (1) statistical models where the geometry of the fracture system is represented by appropriate statistical distributions, and (2) deterministic models, where the geometry of the fracture system is assumed to be known.

The general approach in the statistical work has been to develop an equivalent porous media model that describes the hydraulic behavior of the fracture system. If the rock blocks are porous, it is generally assumed that they provide nearly all of the storage while the fractures are the main conduits (Barenblatt et al., 1960). Important contributions to the statistical approach have been made by Snow (1965) and Romm and Pozinenko (1963). These authors have attempted to develop a permeability tensor to describe the hydraulics of the rock mass. This approach is dependent on determining the fracture aperture distribution, and attempts to do this have been made using the statistics of borehole injection tests (Snow, 1965), photographic techniques on bedrock exposures (Bianchi and Snow, 1968), and elaborate packer tests in multiple injection boreholes (Louis and Pernot, 1972; Louis, 1974). The size of the apertures is a difficult parameter to measure and remains one of the most important factors in any analysis of flow in fractured rock.

Considerable work has been done in the petroleum industry on the movement of oil and gas in fractured reservoirs, and much of this has been of a statistical nature (Freedman and Natanson, 1959; Elkins and Skov, 1960; Zheltov, 1961). Warren and Price (1961) concluded from core analysis and pressure test data that the most probable behavior of single phase flow in a heterogeneous system approaches that of an equivalent homogeneous system having a permeability equal to the geometric mean of the individual permeabilities. Parsons (1966) in studying idealized fracture systems has come to the same conclusion.

Warren and Root (1963) extended this approach to naturally fractured reservoirs using a double-porosity model similar to that of Barenblatt et al. (1960). As shown in Figure 13, the model assumes that two regions of distinctly different porosity exist within the formation. One region, the matrix, has a high storage and low flow capacity, while the other, the fractures, has a low storage and high flow capacity. Recent laboratory work on fractured carbonate rocks (Jones, 1975) shows that fracture systems can contribute materially to the storage capacity.

Variations of this model have been investigated by a number of workers (Pollard, 1959; Odeh, 1965; Kazemi, 1969), and in general, the conclusions reached have not been in agreement. It appears that different results are possible for fractured systems depending upon the reservoir characteristics. For example, a fractured aquifer is equivalent to a homogeneous porous medium if the dimensions of the matrix blocks are small (less than 1 m) and the matrix permeabilities are significant (greater than 10^{-17} m^2 or 0.01 md). Warren and Root (1963) observed that the time required to achieve quasi-steady state flow in a fractured reservoir is one or two orders of magnitude greater than it is in a homogeneous system.

Kazemi (1969) has further extended this approach to unsteady flow in a finite circular reservoir consisting of a set of uniformly spaced horizontal fractures with an intervening permeable matrix and obtained the same results as Warren and Root. In a sequel paper, Kazemi et al. (1969) have attempted to interpret interference tests in naturally

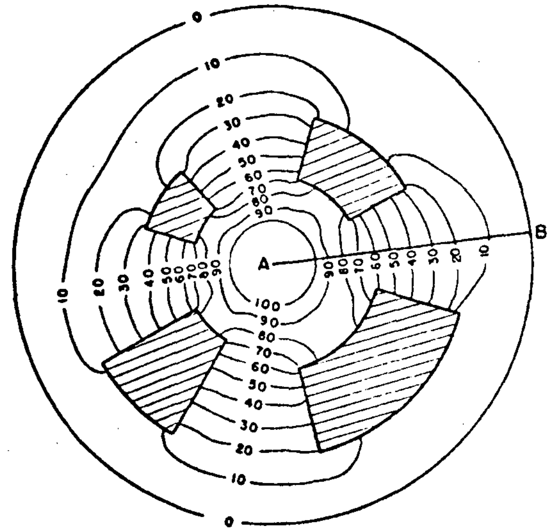

Fig. 12. Pressure distribution with radial flow in a partially closed horizontal fracture.

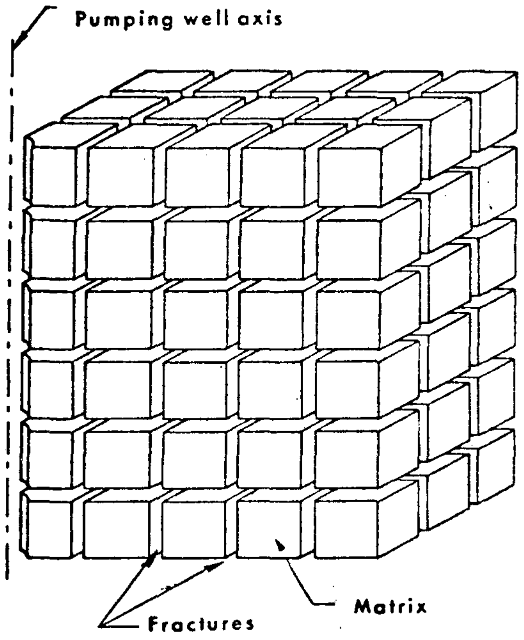

Fig. 13. Double-porosity model for fractured rock masses (after Warren and Root, 1963).

fractured reservoirs assuming a uniform fracture distribution. Results of their analyses demonstrated the marked anisotropy of the reservoir in that for early time responses, an equivalent homogeneous model does not adequately depict the interference effects.

Recently, Duguid (1973) has used a finite element method to model nonsteady flow in porous rocks based on the two-porosity approach of Barenblatt et al. (1960) and the elastic theory of Biot (1940). The fractures are described by a statistical distribution and flow in the fracture system is coupled to that in the porous blocks by a storage equation. Duguid shows how the ratio of fracture permeability to that in the porous blocks affects the time required to reach a steady state fluid pressure distribution.

In the deterministic models, each fracture is modelled separately using an approach based on network analysis. Wilson and Witherspoon (1970) developed a finite element model for discrete fracture systems where the fractures are the principle conductors and are assumed to be rigid. This approach was used to investigate different flow problems such as effect of fracture size on seepage beneath a dam and the effect of tunnel size on groundwater inflow.

Wittke et al. (1972) have also used the finite element model to develop methods of calculating seepage through three-dimensional networks of rigid fractures. They have applied their methods to rock slopes and abutments of a concrete dam. They have also investigated seepage to a tunnel passing through a fractured rock mass and verified their results with a laboratory model.

The decision to use either a deterministic or a statistical model depends on the scale of the structure or area in question relative to the spacing and size of the important discontinuities as well as the ability to collect the appropriate fracture data. Louis and Pernot (1972) have shown how extensive use of drill holes and adits can provide a detailed description of the fracture permeabilities at a dam site. With improved bore hole technology and greater emphasis on seismic safety, we believe that similar field methods can be developed to provide deterministic data on deep fracture systems.

In essentially all of this work on the hydraulic properties of fractures, the assumption has generally been made that the fractures are rigid. However, as has been discussed in connection with mechanical properties, fractures deform with changes in the state of stress. From equations 1 and 2, it is apparent that one should expect significant changes in the fluid flow and pressure distributions as deformations occur. This means that one must consider the interaction of mechanical and hydraulic properties, or what is sometimes termed "stress-flow" behavior of fractures.

INTERACTION OF MECHANICAL AND HYDRAULIC PROPERTIES

Laboratory and Field Results

The mechanical and hydraulic properties of fractures, as outlined in the previous two sections, demonstrate that the fractures are both a highly deformable component of the rock mass and the main flow paths in many impermeable and slightly permeable rocks. Based on Terzaghi's concept of effective stress, an increase of fluid pressure within the plane of fracture will reduce the effective normal stress acting across the fracture. From Figure 2 it can be shown that a reduction in effective normal stress will increase the size of the fracture opening. An increase in aperture will change the flow characteristics of the fracture. Snow (1968) reported results showing that radial and tangential surface ground strains of 10^{-7} to 10^{-8} were measured in a fractured metamorphic rock after the water level in a well had been decreased by 9.1 m. Of importance here is that the strainmeters (25 m long quartz rods) were 75-90 m from the well and there was a two hour delay after the pumping before the strain event occurred.

The effects of stress changes on the storage and permeability of fractured rocks has been discussed by Snow (1968). Increasing fluid pressure during injection tests in fractured rocks will sometimes produce a highly nonlinear pressure-flow rate relationship (Figure 14). This nonlinearity has been attributed (Maini, 1971) to: (a) kinetic energy effects, (b) nonlinear pressure-flow laws, (c) leakage past packers, and (d) increase in fracture aperture. The relative importance of these four factors has not been determined but recent work by Gale (1975) has shown that fracture apertures can be opened or closed significantly by an increase or decrease in fluid pressure. Figure 15 shows part of the results of a laboratory experiment on a large diameter granite core. Fluid injection and withdrawal in the center borehole that intersected two horizontal fractures produced significant changes in aperture. Insitu field measurements also demonstrate that apertures deform under changes in fluid pressure. Figure 16 shows the closing of a fracture located 8.8 m below bedrock surface during fluid withdrawal at a constant rate of 1.5×10^{-4} m^3/s. Fluid injection in the same fracture produced the fracture openings shown in Figure 17. Analysis of these results reveals that the fluid pressures measured in the fracture planes in both the laboratory and field tests could not

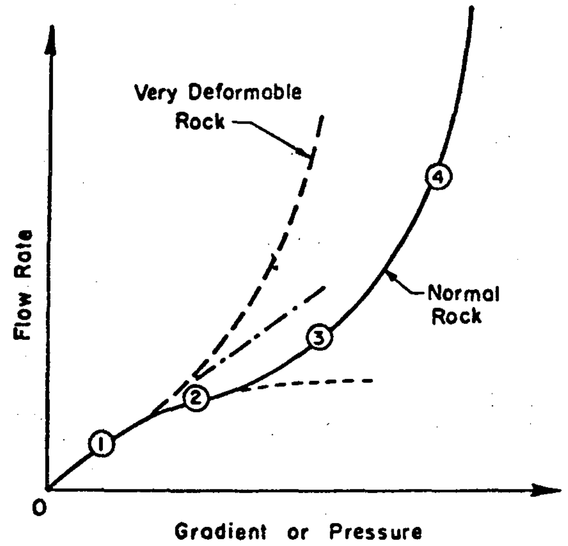

Fig. 14. Typical results of field water injection tests: (1) laminar flow; (2) turbulence effect; (3) turbulence offset by fracture opening; (4) predominance of fracture expansion effects (after Louis and Maini, 1970).

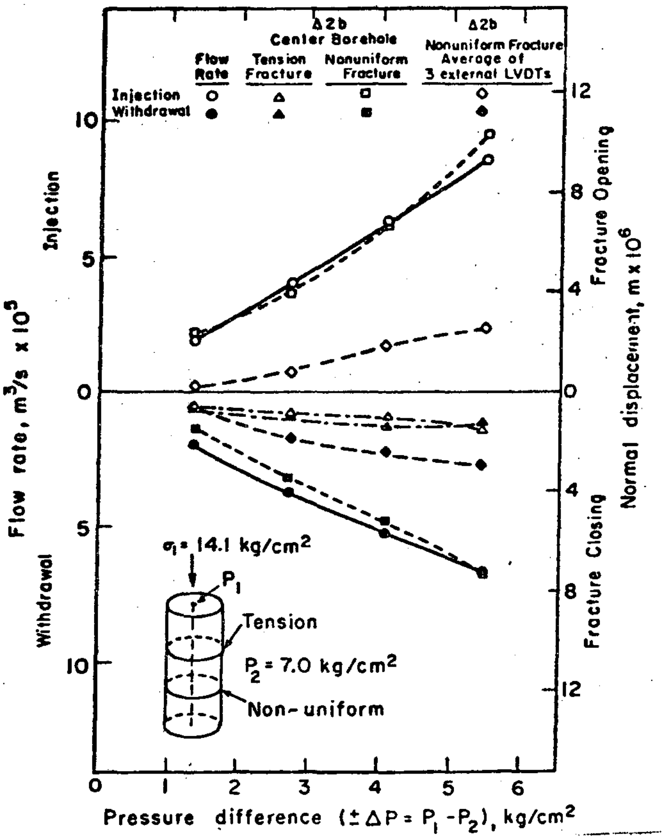

Fig. 15. Effects of injection and withdrawal on two fractures in 0.97 m x 1.8 m granite cylinder with constant axial stress of 14 kg/cm^2 and constant external fluid pressure of 7.03 kg/cm^2 (after Gale, 1975).

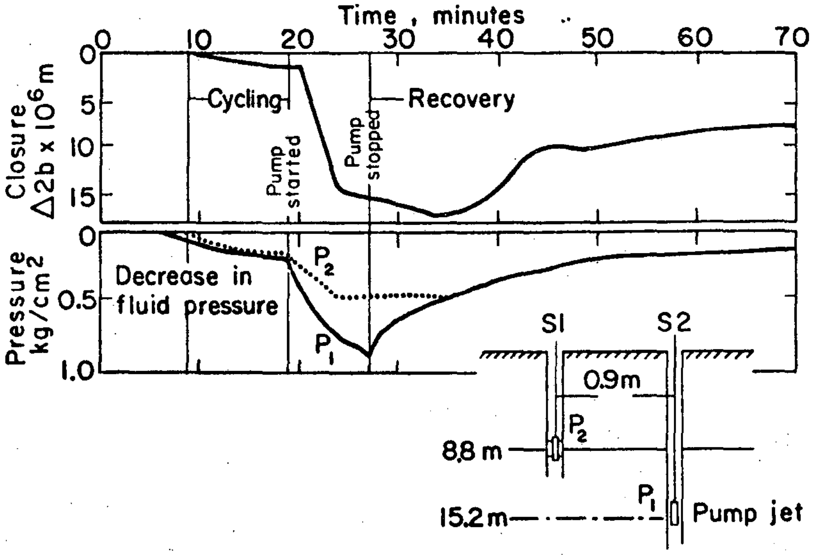

Fig. 16. Field results of withdrawal from borehole S2 on horizontal fracture in quartz monzonite near Sambro, Nova Scotia. Deformations measured across fracture at 8.8 m level in borehole S1 (after Gale, 1975).

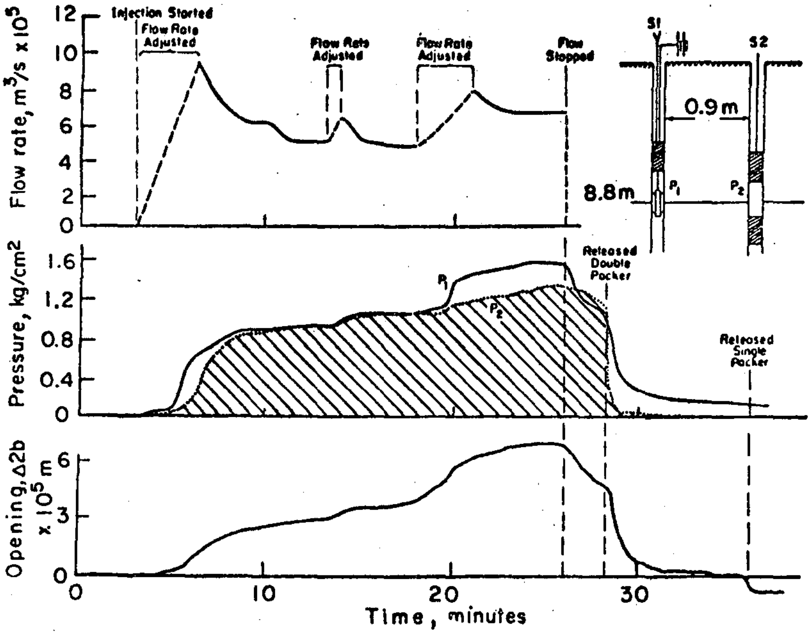

Fig. 17. Field results of injection in borehole S1 on horizontal fracture in quartz monzonite near Sambro, Nova Scotia. Deformations measured across fracture at 8.8 m level in S1 (after Gale, 1975).

have been produced if the fractures had uniform apertures. Uniform apertures would have produced a logarithmic variation of fluid pressure away from the well.

Other fracture deformation measurements by Gale (1975) showed that the magnitude of the aperture change is related in part to the fluid pressure distribution in the fracture plane and hence to the degree of aperture uniformity. If a well intersects a fracture where the aperture is large and if at some distance from the well the aperture then decreases, there will be only a small head loss between the well and the constriction. This would have the effect of propagating fluid pressure changes at the well over a considerable distance. Conversely, when a well intersects the fracture where the aperture is small and the aperture increases at some point away from the well, the area over which the fluid pressures can change would be greatly reduced. This interaction of the mechanical and geometrical properties of fractures with the fluid pressure distributions should be thoroughly investigated when one is considering the possibility of inducing a change in the state of stress around a borehole. Furthermore, a fluid pressure increase in a fracture system reduces the effective normal stress, and as the aperture opens, the deformation decreases the contact area and hence the shear strength of the fracture system.

Bernaix (1967) demonstrated the dependence of the permeability of finely fissured media on the effective normal stress. In a small scale field experiment, Jouanna (1972) has also demonstrated the stress dependent nature of the permeability of finely fissured schist plus the nonrecoverable deformation (hysteresis) with repeated loading. His field results were supported by laboratory tests on similar rock types plus a calcareous rock containing a single fracture. Jouanna's work has been extended by Rayneau (1972) to the study of flow in a single artificial fracture subject to changing external loads. The permeability of discrete fractures was found to have the same stress dependence.

Triaxial tests on saw-cut fractures, where the fracture is subjected to an all around confining pressure showed almost no water flow when the confining pressure exceeded 40 kg/cm^2 (Ohnishi and Goodman, 1974). Similar tests on both artificial and natural fractures (Jones, 1975) revealed that fractures still exhibited permeability to air at 1400 kg/cm^2 confining pressure. At the University of California, radial permeability tests on saw-cut and rough fractures in granitic rock cores have recently been undertaken to determine if a scale effect exists. Iwai (personal communication, 1975) has found that when he subjects a horizontal fracture in a 0.15 m diameter core to a normal stress of about 40 kg/cm^2, the fracture permeability is almost zero. On the other hand, similar tests using a 1 m diameter core have shown that the flow rate quickly reaches a minimum (Figure 18) and thereafter does not decrease significantly even for stresses up to 175 kg/cm^2. In making large scale field tests on natural fractures, Pratt et al. (1974b) has also observed that the fluid flow could not be shut off with increasing normal stress (Figure 19). While this limited number of observations cannot be considered conclusive, there does seem to be some evidence that the larger samples give stress permeability results that are more representative of natural fracture systems because of the effect of bridging and contact area on flow rate.

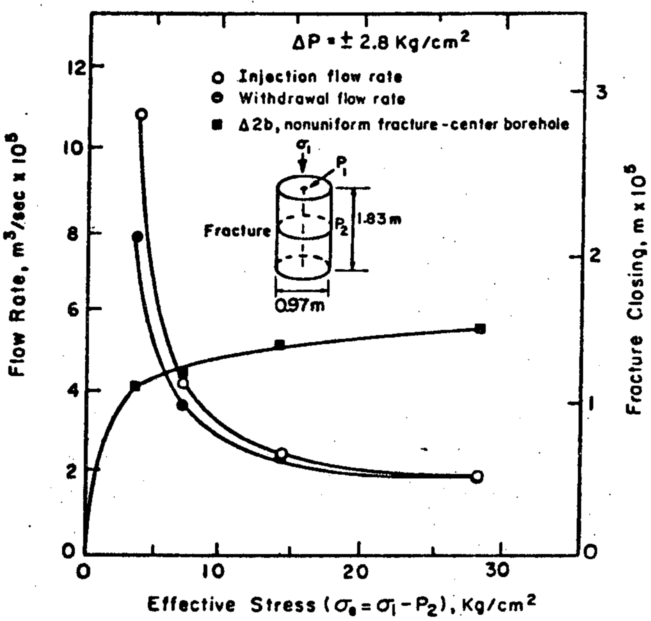

Fig. 18. Flow rate and fracture aperture as a function of effective stress in a horizontal saw-cut fracture in 0.97 m x 1.8 m granite cylinder (after Gale, 1975).

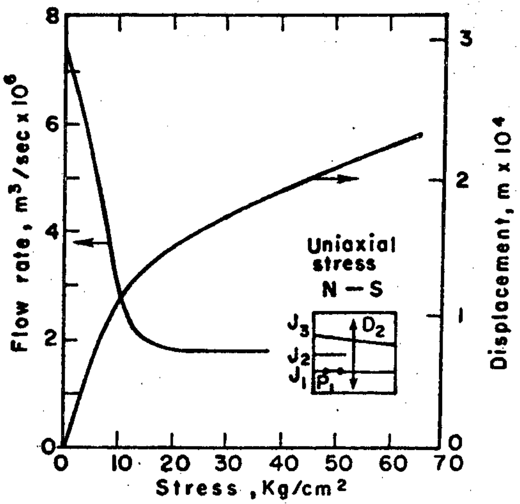

Fig. 19. Comparative diagram showing the effect of stress on displacement and fluid flow in vertical fracture J_1 (after Pratt, et al. 1974b).

Very little data is available on the effects of shear displacement on the permeability of fracture systems. Jouanna (1972) presented results of changing the flow rates as a function of shear stress during shear tests on micaceous schist. The flow rate decreased with increasing stress and was irreversible. Maini (1971) presented the results of a test in which he measured the change in flow rate for known increments of shear displacement along a fracture. The fracture was created by splitting slate parallel to a cleavage plane and the normal load was due to the weight of the sample only. At this low stress level, a shear displacement of 0.01 m and a normal displacement of 0.002 m (opening) produced an increase in permeability of two orders of magnitude. We do not know of any shear test on individual rough fractures performed over a reasonable range of effective normal stresses where the flow rates and both shear and normal displacements were measured during the test. This is an area of research that needs much more work, especially when one considers dilatancy in shear modes.

Ohnishi and Goodman (1974) reported triaxial and direct shear test results where the pore pressure induced in the fractures amounted to ten to fifteen percent of the deviator stress at peak load in the triaxial tests and ten to twenty percent of the peak shear stress during the direct shear tests. This indicates that the effective normal stress in a fracture can be significantly reduced during shear.

Modelling the Interaction of Mechanical and Hydraulic Properties

Two approaches have been used in attempting to numerically model the interaction of fluid pressures and rock stresses in fractured rock masses: (1) continuum models and (2) discrete models. In the continuum models, the properties of the rock blocks and fractures are averaged to give an equivalent continuous medium. This includes combining the permeabilities of the fractures and matrix into an equivalent porous media. In the discrete models, an attempt is made to include the mechanical properties of most of the individual discontinuities as well as that of the rock blocks. The flow characteristics and geometry of the individual fractures are assumed to dominate the flow field and are treated in a manner essentially the same as that of the deterministic models described earlier.

There is a basic argument as to whether the continuum or discrete approach should be used. Both approaches have certain advantages and disadvantages. The continuum approach only needs information as to the average values of fracture spacing and material properties. But as pointed out earlier, with increase in complexity of the fracture geometry and the corresponding decrease in symmetry of the system, it becomes more difficult to develop an equivalent continuum that will simulate the behavior of the fractured rock mass. Also, after replacing the rock mass by an equivalent continuum, failure cannot occur until a new fracture develops.

Riney et al (1973) have used the continuum approach and make shear strength dependent on the spacing and frictional properties of the fracture system. With regard to the concept of induced seismicity, this presents a problem because one is unable to look at failure conditions along some pre-existing plane of weakness, such as a fault zone. Dieterich et al. (1972), in a study of earthquake triggering by fluid injection, avoids this problem by combining a continuum description of of the rock block bounding a fault zone with a detailed description of the zone itself. Both the static and dynamic friction were allowed to vary with location and as a function of changes in fluid pressures within the fault zone. Using field and laboratory input data, Dietrich et al. have obtained results that compare favorably with the earthquake activity observed during field experiments at Rangely, Colorado.

Morgenstern and Guther (1972) used two finite element codes: (1) a two-dimensional, equivalent porous media code to model flow in fractured rock slopes, and (2) a two-dimensional code of a linearly elastic medium to model the stresses in the rock slopes. The two programs were coupled through the stress dependent nature of the permeability. Results presented by the authors show the effects of different stress configurations on the pressure distribution and permeability in excavated slopes. Morgenstern and Guther based their use of this simplified model on the fact that available experimental data did not justify the study of more complex relationships.

This lack of input data has been considered a serious limitation of discrete models. This is no longer a valid criticism. As indicated above, Louis and Pernot (1972) have shown how improved borehole techniques enable one to obtain a three-dimensional picture of the geometry and hydraulic properties of the fracture system. The mechanical properties of individual fractures can be determined from careful insitu and laboratory tests. We fully appreciate the problems inherent in applying such an approach to deeply buried fracture systems, but as has been pointed out by Raleigh (1972), one needs to know to what degree generalization of the fracture geometry can be made without seriously degrading the calculational results.

Discrete models of fractured rock masses have been developed by Rodatz and Wittke (1972) and Noorishad et al. (1971). Noorishad et al. combined two finite element programs: (1) a steady state, line element program to model flow through the fractures, and (2) a plane strain structural program incorporating joint elements to model displacements and stresses within the rock mass. The fluid pressures interact with other stresses acting on the rock blocks simulating a coupled stress-flow phenomena. Noorishad et al.(1972) have demonstrated the feasibility of using this model to study the effects of fluid pressures on changes in fracture apertures. Gale et al. (1974) have modified this approach in order to model general two-dimensional plane strain and axisymmetric problems with arbitrary orientations of the fracture network and of the initial stress field. This numerical model is essentially quasi-static.

The model of Gale et al. (1974) has been applied by Witherspoon et al. (1974) to studies of the parameters that affect controlled displacements along the fracture planes within a fault zone during fluid injection and withdrawal through wells. As shown in Figure 20, these investigations have revealed that the areas over which fluid pressures are increased (and hence the effective stress decreased) during injection can be considerably larger than the areas over which pressures are decreased (and hence the effective stress increased) by fluid withdrawal. In this study, permeability anisotropy within the fault zone was assumed to be an important factor. Fracture apertures parallel to the axis of the fault were always 3.0×10^{-4}m while the initial values of those oriented normal to the fault axis were allowed to vary from $3.0 \times 10^{-5}$to 2.4×10^{-4} m. The large variation in areas affected (Figure 20) reflects the effects of changing the permeability anisotropy within the fault zone and the fact that the opening and closing of fractures has a non-linear effect on fluid pressure distributions.

Witherspoon et al. (1974) have also investigated the effect of the orientation of the initial principle stress vector on the length of the failure zone induced by fluid injection at one point in a fault zone. Figure 21 shows results for five different stress orientations and two different injection pressures. The orientation shown is the angle between the maximum principal stress and the axis of the fault zone. At either injection pressure, the maximum length of shear failure occurs when the principal stress makes an angle of $45° - \phi/2$ with the direction of the fault plane, where ϕ is the angle of static friction within the fracture. In this work, we assumed $\phi = 38°$, and it will be noted that maximum shear failure occurred with $\alpha \approx 26°$. These results correspond with the continuum relationships in rock mechanics. Since the fault zone contained an orthogonal network of fractures, it would be of interest to determine if this relationship could still hold in a nonorthogonal system of fractures where interlocking of rock blocks could occur.

Current numerical modelling work at the University of California, Berkeley, consists of developing coupled-stress, nonsteady-flow models of fractured porous media. In addition, dynamic coupled stress-flow models of fractured media are also being developed. The purpose is to permit an evaluation of the importance of the different geometric, mechanical, and hydraulic parameters of fracture systems on pre-failure conditions as well as the role they play in failure and post-failure events.

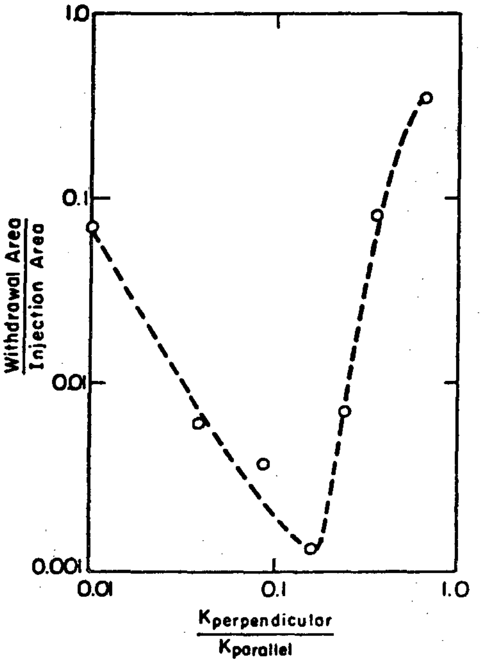

Fig. 20. Effect of fracture permeability anisotropy within fault zone on areas affected by fluid injection and withdrawal (after Witherspoon, et al., 1974).

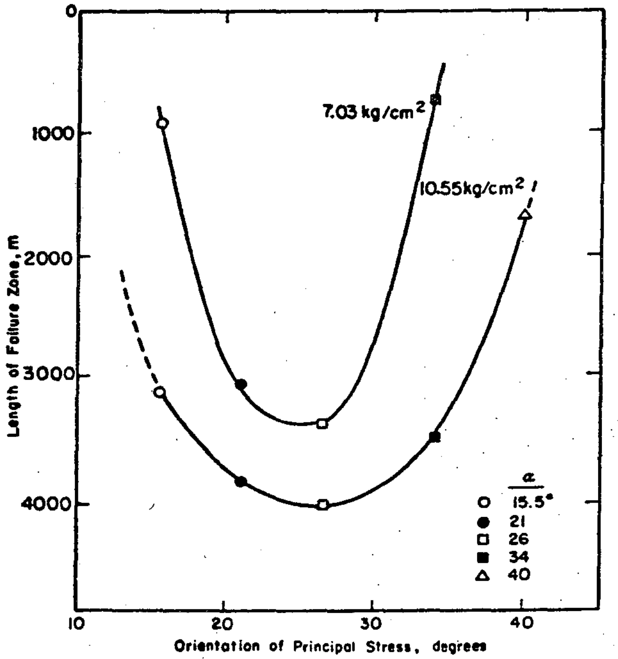

Fig. 21. Effect of orientation of maximum principal stress and injection pressure on length of shear failure along fracture parallel to axis of fault zone (after Witherspoon et al., 1974).

CLOSURE

As indicated in this review, there is no general agreement on how the various fracture parameters should be described, how they should be measured, or how they should be used in the analysis of fractured rock masses. Fractures are both the dominant flow paths as well as the weakest links in most rock masses, and their behavior is highly non-linear. In addition, there is some evidence that in laboratory determinations of fracture properties, there is an apparent scale effect in terms of sample size.

Existing and developing borehole and laboratory techniques provide a means for obtaining a three-dimensional picture of the mechanical and hydraulic properties of shallow fracture systems. The possibility of extending these methods to deeper fracture systems needs more investigation. Such data must be considered when one is deciding whether to use a continuum or discrete model to represent the interaction of rock and fluid forces in a fractured rock system, especially with regard to the problem of induced seismicity. When one is attempting to alter the pressure distribution in a fault zone by injection or withdrawal of fluids, the extent to which this can be achieved will be controlled in large measure by the behavior of the fractures that communicate with the borehole. Since this is essentially a point phenomena, i.e. the changes will propagate from a relatively small region around the borehole, the use of a discrete model would appear to be preferable.

ACKNOWLEDGMENTS

We would like to acknowledge support for this work from the U. S. Energy Research and Development Administration, the National Science Foundation and the U. S. Geological Survey.

REFERENCES

Banks, D. C., 1972, "In Situ Measurements of Permeability in Basalt," Proceedings Symposium on Percolation through Fissured Rock, International Society for Rock Mechanics, Stuttgart, n. T1A, pp. 1-6.

Barenblatt, G., Zheltov, U. P., and Kochina, G. H., 1960, "Basic Concepts in the Theory of Seepage of Homogeneous Liquids in Fissured Rocks," in Prikladnaya Matem, i Mekh, v. 24, pp. 852-864 (in Russian).

Barton, N. R., 1971, A Model Study of the Behaviour of Steep Excavated Rock Slopes, Ph.D. Thesis, Imperial College.

Barton, N., 1973, "Review of a New Shear Strength Criterion for Rock Joints," Engineering Geology, v. 7, pp. 287-332.

Barton, N., 1974, "Estimating the Shear Strength of Rock Joints," Proceedings Third Congress International Society of Rock Mechanics, Denver, v. II-A, pp. 219-220.

Bernaix, J., 1967, Etude Geotechnique de la Roche de Malpasset, Paris, Dunod, p. 215.

Bernaix, J., 1969, "New Laboratory Methods of Studying the Mechanical Properties of Rocks," International Journal of Rock Mechanics and Mining Science, v. 6, pp. 43-90.

Bianchi, L. and Snow, D. T., 1968, "Permeability of Crystalline Rock Interpreted from Measured Orientations and Apertures of Fractures," Annals of Arid Zone, v. 8, n. 2, pp. 231-245.

Bieniawski, Z. T., 1968, "Propagation of Brittle Fracture in Rock," Proceedings of the Tenth Symposium on Rock Mechanics, AIME, Chapter 15.

Biot, M. A., 1940, "General Theory of Three-Dimensional Consolidation," Journal of Applied Physics, v. 12, pp. 155-164.

Bishop, A. W., 1974, "The Strength of Crustal Materials," Engineering Geology, v. 8, pp. 139-153.

Brace, W. F., 1974, "Experimental Studies of Seismic Behaviour of Rocks under Crustal Conditions," Engineering Geology, v. 8, pp. 109-127.

Brace, W. F., Paulding, Jr., B. W. and Scholz, C. H., 1966, "Dilatancy in the Fracture of Crystalline Rocks," Journal of Geophysical Research v. 71, pp. 3939-3953.

Byerlee, J. D., 1967, "Frictional Characteristics of Granite under High Confining Pressure," Journal of Geophysical Research, v. 72, p. 3639.

Byerlee, J. D. and Brace, W. F., 1968, "Stick-Slip, Stable Sliding and Earthquakes, Part 1. Effect of Rock Type, Pressure, Strain-Rate, and Stiffness," Journal of Geophysical Research, v. 73, n. 18, p. 6031.

Coulson, J. H., 1970, "The Effects of Surface Roughness on the Shear Strength of Joints in Rock," Army Corps of Engineers Technical Report MRD-1-70, Omaha, Nebraska, p. 283.

Dieterich, J. H., 1972, "Time-Dependent Friction as a Possible Mechanism for Aftershocks," Journal of Geophysical Research, v. 77, n. 20, pp. 3771-3781.

Dieterich, J. H., Raleigh, C. B., and Bredehoeft, J. D., 1972, "Earthquake Triggering by Fluid Injection at Rangely, Colorado," Proceedings Symposium on Percolation through Fissured Rock, International Society for Rock Mechanics, Stuttgart, n. T2B, pp. 1-12.

Duguid, J. O., 1973, Flow in Fractured Porous Media, Ph.D. Thesis, Princeton University.

Elkins, L. F. and Skov, A. M., 1960, "Determination of Fracture Orientation from Pressure Interference," Transactions AIME, v. 219, p. 301.

Franklin, J., Manailoglou, J. and Sherwood, D., 1974, "Field Determination of Direct Shear Strength," Proceedings Third Congress International Society for Rock Mechanics, v. IIA, pp. 233-240.

Freedman, H. A. and Natanson, S. G., 1959, "Recovery Problems in a Fracture-Pore System, Kirkuk Field," Proceedings Fifth World Petroleum Congress, v. 2, p. 297.

Gale, J. E., 1975, A Numerical Field and Laboratory Study of Flow in Rocks with Deformable Fractures, Ph.D. Thesis, University of California, Berkeley, 255 pp.

Gale, J. E., Taylor, R. L., Witherspoon, P. A., and Ayatollahi, M. S., 1974, "Flow in Rocks with Deformable Fractures," in Finite Element Methods in Flow Problems, edited by J. T. Oden, O. C. Zienkiewicz, R. H. Gallagher and C. Taylor, UAH Press, The University of Alabama in Huntsville, Alabama, pp. 583-598.

Goodman, R. E., 1970, "The Deformability of Joints," in Determination of the In-Situ Modulus of Deformation of Rock - ASTM STP 477, pp. 174-196.

Goodman, R. E., 1974, "The Mechanical Properties of Joints," Proceedings Third Congress International Society for Rock Mechanics, Denver, v. IA, pp. 127-140.

Goodman, R. E. and Dubois, J., 1972, "Duplication of Dilatancy in Analysis of Jointed Rocks," Journal of Soil Mechanics and Foundations Division, Proceedings ASCE, v. 98, n. SM4, pp. 399-422.

Goodman, R. E. and Duncan, J. M., 1971, "The Role of Structure and Solid Mechanics in the Design of Surface and Underground Excavations in Rock," Proceedings Conference on Structure, Solid Mechanics and Engineering Design, Part 2, paper 10, pp. 1379-1404.

Goodman, R. E. and Ohnishi, Y., 1973, "Undrained Shear Tests on Jointed Rock," Rock Mechanics, v. 5, n. 3, pp. 129-149.

Goodman, R. E., Taylor, R. L. and Brekke, T., 1968, "A Model for the Mechanics of Jointed Rock," Journal of Soil Mechanics and Foundations Division, ASCE, v. 98, n. SM4.

Gringarten, A. C. and Ramey, H. J., 1974, "Unsteady-State Pressure Distributions Created by a Well with a Single Horizontal Fracture, Partial Penetration, or Restricted Entry," Society of Petroleum Engineers Journal, August 1974, pp. 413-426.

Gringarten, A. C., Ramey, H. J., and Raghavan, R., 1974, "Unsteady-State Pressure Distributions Created by a Well with a Single Infinite-Conductivity Vertical Fracture," Society of Petroleum Engineers Journal, August 1974, pp. 347-360.

Gringarten, A. C. and Witherspoon, P. A., 1972, "A Method of Analyzing Pump Test Data from Fractured Aquifers," Proceedings Symposium on Percolation through Fissured Rock, International Society for Rock Mechanics, Stuttgart, n. T3-B, pp. 1-9.

Hantush, M. S., 1966, "Wells in Homogeneous Anisotropic Aquifers," Water Resources Research, v. 2, n. 2, pp. 273-279.

Hodgson, R. A., 1961a, "Regional Study of Jointing in Comb Ridge, Navajo Mountain Area, Arizona and Utah," AAPG Bulletin, v. 45, p. 1.

Hodgson, R. A., 1961b, "Classification of Structures on Joint Surfaces," American Journal of Science, v. 259, pp. 493-502.

Hoek, E. and Pentz, D. L., 1969, "Review of the Role of Rock Mechanics Research in the Design of Open-Cast Mines," Proceedings Ninth International Congress Mining Metallurgy, London.

Jaeger, J. C., 1959, "The Frictional Properties of Joints in Rocks," Geofisica Pura Applicata, v. 43, pp. 148-158.

Jaeger, J. C., 1971, "Friction of Rocks and Stability of Rocl Slopes," Geotechnique, v. 21, n. 2, pp. 97-134.

Jaeger, J. C. and Cook, N. G. W., 1969, Fundamentals of Rock Mechanics, Methuen and Co., Ltd, London.

Jones, F. O., 1975, "A Laboratory Study of the Effects of Confining Pressure on Fracture Flow and Storage Capacity in Carbonate Rocks," Journal of Petroleum Technology, January 1975, pp. 21-27.

Jouanna, P., 1972, Effect des Sollicitations Mecaniques sur les Ecoulements dans Certains Milieux Fissures, Docteur ES-Sciences Physiques These, l'Universite de Toulouse, France.

Kazemi, H., 1969, "Pressure Transient Analysis of Naturally Fractured Reservoirs with Uniform Fracture Distribution," Society of Petroleum Engineers Journal, v. 9, n. 4, pp. 451-462.

Kazemi, H., Seth, M. S., and Thomas, G. W., 1969, "The Interpretation of Interference Tests in Naturally Fractured Reservoirs with Uniform Fracture Distribution," Society of Petroleum Engineers Journal, v. 9, n. 4, p. 463.

Kiràly, L., 1969, "Statistical Analysis of Fractures - Orientation and Density," Sonderdruck aus der Geologischen Rundschau, Band 59, n. 1, pp. 125-151.

Krsmanovic, D., 1967, "Initial and Residual Shear Strength of Hard Rocks," Geotechnique, v. 17, n. 2, pp. 145-160.

Ladanyi, B. and Archambault, G., 1970, "Simulation of Shear Behavior of Jointed Rock Mass," Proceedings Eleventh Symposium on Rock Mechanics, AIME, pp. 83-104.

Lajtai, E. Z., 1975, "Failure along Planes of Weakness," Canadian Geotechnical Journal, v. 12, pp. 118-125.

Lane, K. S., 1969, "Engineering Problems Due to Fluid Pressure in Rock," Proceedings Eleventh Symposium on Rock Mechanics, AIME, pp. 501-540.

Locher, H. G., 1968, "Some Results of Direct Shear Tests on Rock Discontinuities," Proceedings Second International Symposium Rock Mechanics, Madrid, v. 1, pp. 171-173.

Lomize, G. M., 1951, "Fluid Flow in Fractured Rocks," Gosenergoizdat, Moscow (in Russian).

Louis, C., 1969, "A Study of Groundwater Flow in Jointed Rock and Its Influence on the Stability of Rock Masses," Rock Mechanics Research Report No. 10, Imperial College of Science and Technology, London.

Louis, C., 1974, "Rock Hydraulics," Bureau de Recherches Geologiques et Mineres, Orléans.

Louis, C. and Maini, Y. N. T., 1970, "Determination of In Situ Hydraulic Parameters in Jointed Rock," Proceedings Second Congress International Society Rock Mechanics, Belgrade, pp. 1-32.

Louis, C. and Pernot, M., 1972, "Three-Dimensional Investigation of Flow Conditions of Grand Maison Damsite," Proceedings Symposium on Percolation through Fissured Rock, International Society Rock Mechanics, Stuttgart, n. T4-F, pp. 1-16.

Mahtab, M. A., Bolstad, D. D., Alldredge, J. R., and Shanely, R. J., 1973, "Analysis of Fracture Orientations for Input to Structural Models of Discontinuous Rock," U. S. Bureau of Mines Report of Investigation No. 7669.

Maini, Y. N. T., 1971, In Situ Hydraulic Parameters in Jointed Rock - Their Measurement and Interpretation, Ph.D. Thesis, Imperial College, University of London, 312 pp.

Morgenstern, N. R. and Guther, H., 1972, "Seepage into an Excavation in a Medium Possessing Stress-Dependent Permeability," Proceedings Symposium on Percolation through Fissured Rock, International Society Rock Mechanics, Stuttgart, n. T2-C, pp. 1-12.

Noorishad, J., Witherspoon, P. A. and Brekke, T. L., 1971, "A Method for Coupled Stress and Flow Analysis of Fractured Rock Masses," Geotechnical Engineering Publication No. 71-6, University of California, Berkeley, 128 pp.

Noorishad, J., Witherspoon, P. A. and Maini, Y. N. T., 1972, "The Influence of Fluid Injection on the State of Stress in the Earth's Crust," Proceedings Symposium on Percolation through Fissured Rock, International Society Rock Mechanics, Stuttgart, n. T2-H, pp. 1-11.

Nur, A., 1974, "Tectonophysics: The Study of Relations between Deformation and Forces in the Earth," Proceedings Third Congress International Society Rock Mechanics, Denver, v. IA, pp. 243-317.

Odeh, A. S., 1965, "Unsteady-State Behavior of Naturally Fractured Reservoirs," Society of Petroleum Engineers Journal, March 1965, pp. 60-66.

Ohnishi, Y., 1973, Laboratory Measurement of Induced Water Pressures in Jointed Rocks, Ph.D. Thesis, University of California, Berkeley, 277 p.

Ohnishi, Y. and Goodman, R. E., 1974, "Results of Laboratory Tests on Water Pressure and Flow in Joints," Proceedings Third Congress International Society Rock Mechanics, Denver, v. IIA, pp. 660-666.

Ollos, G., 1963, "Examen Hydraulique de l'Ecoulement dans des Roches Crevassées sur des Modeles Réduits," Bulletin IASH, v. 8, n. 2, p. 9.

Papadopulos, I. S., 1967, "Nonsteady Flow to a Well in an Infinite Anisotropic Aquifer," Proceedings Dubrovnik Symposium on Hydrology of Fractured Rocks, IASH, v. 1, n. 73, pp. 21-31.

Parsons, M. L., 1972, "Determination of Hydrogeological Properties of Fissured Rocks," Proceedings Twenty-fourth Geological Congress, Montreal, Canada, Section II, Hydrogeology, pp. 89-99.

Parsons, R. W., 1966, "Permeability of Idealized Fractured Rock," Society of Petroleum Engineers Journal, June 1966, pp. 126-136.

Patton, F. D., 1966, Multiple Modes of Shear Failure in Rock and Related Materials, Ph.D. Thesis, University of Illinois.

Pollard, P., 1959, "Evaluation of Acid Treatments from Pressure Build-up Analysis," Transactions, AIME, v. 216, pp. 38-43.

Pratt, H. R., Black, A. D., Brown, W. S. and Brace, W. F., 1972, "The Effect of Specimen Size on the Mechanical Properties of Unjointed Diorite," International Journal Rock Mechanics and Mining Science, v. 9, pp. 513-529.

Pratt, H. R., Black, A. D., Brown, W. S. and Brace, W. F., 1974a, "A New Technique for Determining the Deformation and Frictional Characteristics of In Situ Rock," Field Testing and Instrumentation of Rock, ASTM STP 554, American Society for Testing and Materials, pp. 3-19.

Pratt, H. R., Swolfs, H. S. and Black, A. D., 1974b, "Properties of In Situ Jointed Rock," Final Technical Report to Environmental Sciences Division, U. S. Army Research Office, Durham, North Carolina under Contract No. DAH C04 72 C 0049, Terratek, Sal Lake City, 19 pp.

Raleigh, C. B., 1972, "Mechanical Behavior of Fissured Rock Due to Percolation; Man-Made Earthquakes," General Report Theme 2, Proceedings Symposium on Percolation through Fissured Rock, International Society for Rock Mechanics, Stuttgart, n. G2, pp. 1-11.

Raleigh, C. B., Healy, J. H. and Bredehoeft, J. D., 1972, "Faulting and Crustal Stress at Rangely, Colorado," in Flow and Fracture of Rocks, AGU Geophysical Monograph, n. 16, pp. 275-284.

Ramey, H. J., 1970, "Short-Time Well Test Data Interpretation in the Presence of Skin Effect and Wellbore Storage," Journal Petroleum Technology, January 1970, pp. 97-104.

Rayneau, C., 1972, Contribution a l'Etude des Ecoulements Autom d'un Forage en Milieu Fissure, These, Docteur-Ingenieur Universite des Sciences et Technique du Languedoc, Academie de Montpellier, France, 77 pp.

Rengers, N., 1970, "Influence of Surface Roughness on the Friction Properties of Rock Planes," Proceedings Second Congress International Society Rock Mechanics, Belgrade, pp. 1-31.

Riney, T. D., Frazier, G. A., Garg, S. K., Good, A. J., Herrmann, R. G., Morland, L. W., Pritchett, J. W., Rice, M. H. and Sweet, J., 1973, "Constitutive Models and Computer Techniques for Ground Motion Predictions," Final Report, Contract No. DASA 01-69-C-0159 (P004), Defense Advanced Research Projects Agency, Arlington, Virginia 22209, p. 357.

Rocha, M., 1964, "Mechanical Behaviour of Rock Foundation in Concrete Dams," Transactions Eighth Congress Large Dams, Edinburgh, pp. 785-831.

Rodatz, W. and Wittke, W., 1972, "Wechselwirkung zwischen Deformation and Durchströmung in Klüftigen, Anisotropen Gebirge," Proceedings Symposium on Percolation through Fissured Rock, International Society for Rock Mechanics, Stuttgart, n. T2, pp. 1-5.

Romm, E. S., 1966, "Fluid Flow in Fractured Rocks," Nedra, Moscow (in Russian).

Romm, E. S. and Pozinenko, B. V., 1963, "Investigation of Seepage in Fractured Rocks," Trudy VNIGRI, n. 214, Leningrad (in Russian).

Rosengren, K. J., 1968, Rock Mechanics of the Black Star Open Cuts, Mt. Isa, Ph.D. Thesis, Australian National University, Canberra.

Sharp, J. C., 1970, Fluid Flow Through Fissured Media, Ph.D. Thesis, Imperial College of Science and Technology, London, 200 pp.

Shehata, W. M., 1971, Geohydrology of Mount Vernon Canyon Area, Jefferson County, Colorado, Ph.D. Thesis, Colorado School of Mines, Golden, Colorado.

Snow, D. T., 1965, A Parallel Plate Model of Fractured Permeable Media, Ph.D. Thesis, University of California, Berkeley, 331 pp.

Snow, D. T., 1968, "Fracture Deformation and Changes of Permeability and Storage upon Changes of Fluid Pressure," Quarterly Colorado School of Mines, v. 63, n. 1, p. 201.

Snow, D. T., 1972, "Fundamentals and In Situ Determination of Permeability," General Report Theme 1, Proceedings Symposium on Percolation through Fissured Rock, International Society for Rock Mechanics, Stuttgart, n. G1, pp. 1-6.

Warren, J. E., and Price, H. S., 1961, "Flow in Heterogeneous Porous Media," Society Petroleum Engineers Journal, September, pp. 153-169.

Warren, J. E. and Root, P. J., 1963, "The Behavior of Naturally Fractured Reservoirs," Transactions AIME, v. 228, pp. 245-255.

Wilson, C. R. and Witherspoon, P. A., 1970, "An Investigation of Laminar Flow in Fractured Rocks," Geotechnical Report No. 70-6, University of California, Berkeley, 178 pp.

Witherspoon, P. A., Gale, J. E., Taylor, R. L. and Ayatollahi, M. S., 1974, "Investigation of Fluid Injection in Fractured Rock and Effect on Stress Distribution," Annual Report for period March 13, 1973 through June 12, 1974, to U. S. Geological Survey under Contract 14-08-001-12727, ARPA Order No. 1648, 96 pp.

Wittke, W., Rissler, P., and Semprich, S., 1972, "Räumliche, Laminare und Turbulente Strömung in Klüftigen Fels nach Zwei Verschiedenen Rechnenmodellen," Proceedings Symposium on Percolation through Fissured Rock, International Society for Rock Mechanics, Stuttgart, n. T1-H, pp. 1-18.

Zheltov, U. P., 1961, "On Single-Phase Liquid Flow through Deformed Fractured Non-Porous Rocks," Applied Mathematics and Technical Physics, n. 6, USSR.

Zienkiweicz, O. C. and Stagg, K. G., 1966, "The Cable Method of In Situ Testing," Proceedings First Congress International Society for Rock Mechanics, v. 1, pp. 667-672.

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720