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Author
Witherspoon, P. A.

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Lawrence Berkeley Laboratory
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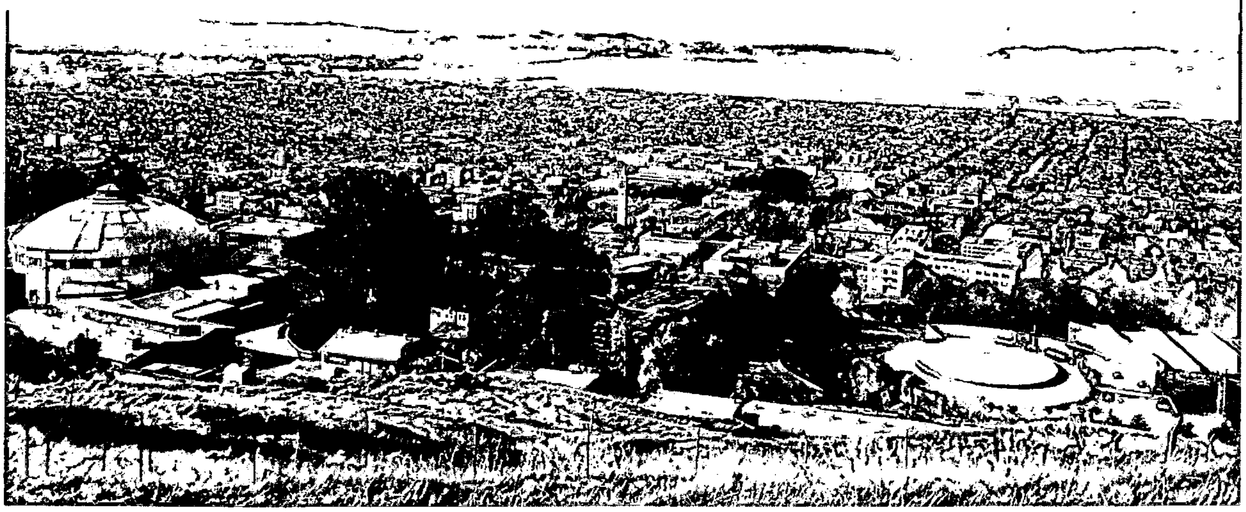

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EFFECT OF SIZE ON FLUID MOVEMENT IN ROCK FRACTURES

Paul A. Witherspoon

Lawrence Berkeley Laboratory and Department of Materials Science
and Mineral Engineering, University of California, Berkeley, 94720

Abstract. Laboratory studies on fluid flow in single fractures in rock samples up to a meter in size suggest that there is a definite problem of scale. Two such studies have been reported, but the results are not consistent. The seemingly contradictory results may simply be a manifestation of the effects of fracture surface roughness. A basic problem in attempting to understand the physics of fluid flow in fractures is that of understanding the effects of surface roughness. The investigations that are envisioned to attack this problem will only be possible on rock samples that are much larger than the conventional size.

Introduction

The movement of fluids through fractures in rock systems and the factors that affect such movement are matters of fundamental importance to the earth sciences. The exploitation of mineral resources, the isolation of waste products in underground structures, and the construction of engineering works are only a few of the fields of interest where flow in fractures is an important, if not controlling factor. One would prefer to study such problems in the field, but to understand discontinuous rock systems requires a level of detailed knowledge on fracture geometry and boundary conditions that is not easily acquired.

A common approach to this problem is to take rock samples containing fractures to the laboratory and set up a system where fluid movement in a single fracture can be investigated under controlled conditions. The size of such samples has usually been 10 to 15 cm or less, and the results of a fair amount of work are now available in the literature [Brace, et al., 1966; Iwai, 1976; Kranz et al.,1979; Trimmer et al., 1980]. The question with regard to the size effect is then the following: Is the knowledge gained from flow experiments done on such small size samples transferable to real rock masses in the field? Some of these investigations have been used to examine the applicability of the so called "cubic law" for flow in a single fracture, which is given by

$$Q/\Delta h = C(b)^3 \qquad (1)$$

where $Q/\Delta h$ is the flow through the fracture per unit change in hydraulic head, b is the fracture aperture, and C is a constant that depends on geometry of the flow field and fluid properties. For linear flow through a rectangular sample of length L and width W

$$C = - W/L\ (\rho g/12\mu) \qquad (2)$$

where ρ, g, and μ are, respectively, the fluid density, the acceleration of gravity, and fluid viscosity. For radial flow in a cylindrical sample of radius r_e and well bore radius r_w,

$$C = -[2\pi/\ell n(r_e/r_w)]\ (\rho g/12\mu) \qquad (3)$$

The important point to keep in mind is that the cubic law was derived for an aperture bounded by parallel planar plates in which b is uniform over the field of flow (Boussinesq, 1868; Lomize, 1951; Snow, 1965; Romm, 1966; Bear, 1972). Theoretically, there is no effect of size, at least for the range of apertures that are likely to be encountered in the field. In fact, the cubic law has been investigated in the laminar flow regime using optically flat surfaces and various liquids and found to hold for apertures as small as 0.2 m (Romm, 1966). This is well below the minimum values (10 to 100 μm) reported for open fractures in rock systems (Gale, 1975).

The Basic Problem

The basic problem in attempting to apply the cubic law to real fractures is that of understanding the effects of surface roughness (Gangi, 1978; Walsh and Grosenbaugh, 1979; Kranz, *et al*., 1979). We have recently been attempting to use a concept as portrayed in Figure 1 to characterize a rough fracture in terms of an array of apertures whose magnitudes depend on the heights of the asperities (Tsang and Witherspoon, 1981). The tallest asperities are contacted by rock when a fracture first begins to close. As normal stress increases, more points of contact develop with the result that a plot of stress versus fracture deformation exhibits a highly non-linear behavior (Figure 2). One can hypothesize that as the fracture closes, the aperture decreases in size and the modulus of the fracture increases to approach that of intact rock as more and more asperities come in contact.

Such an approach requires a modification of the cubic law in equation 1. The constant value for b must be replaced by an appropriate statistical average for the variable aperture (Tsang and Witherspoon, 1981). Two fundamental questions immediately arise from such a model: (1) Assuming a modified cubic law can be found that realistically describes fluid movement through the rough walled fracture, will such an expression continue to hold for fluid flow through the fracture as it undergoes deformation regardless of size? and (2) Over what size of a fracture surface must measurements be made to have results for hydraulic conductivity as a function of stress that are representative of the true situation in the field? Work to date does not provide adequate answers for either of these important questions.

Some laboratory studies of flow in single fractures in rock samples ranging up to a meter in size suggest that there is a definite problem of scale. Two such studies have been reported, but the results are not consistent. In one case, the conclusion was reached that hydraulic conductivity of a fracture at a given stress level decreased as the size of the sample decreased (Witherspoon _et al_., 1979). In another more recent investigation using samples ranging in size from 10 to 30 cm, the opposite effect was found (Gale and Raven, 1981). Since both studies assumed the validity of the cubic law as expressed in equation 1, it is conceivable that the seemingly contradictory conclusions are simply a manifestation of the effects of fracture surface roughness, which could very well show up in the different size samples in a completely unsystematic fashion. This underlines the fundamental question posed earlier: Does there exist an optimum size for a fracture surface above which the apparent size effect is no longer important, and on which laboratory measurements may be made to give results that are representative of the situation in the field? Much more work is needed to resolve this problem.

The question of the applicability of the parallel-plate cubic law to flow in fractures is also unresolved, even though significantly more work has been carried out on this second problem Romm, 1966; Lomize, 1951). In some cases, evidence for the applicability of the cubic law, especially to tension fractures that were newly induced in crystalline rock, is quite convincing

(Witherspoon et al., 1980). However, other investigations on natural fractures, where the effects of weathering were present (Gale and Raven, 1981) or on fresh rock fractures that were arbitrarily roughened in varying amounts (Kranz, et al. 1979) have produced mixed results. Only partial agreement with the cubic law has been reported. In these studies the fracture apertures as a function of applied load were not measured directly, but were derived from rock displacement measurements made across the fracture. The effect of roughness was not included in that a single value for the aperture was used, and furthermore, the applied stress was assumed to be uniform across the entire fracture. Not enough is known either to justify or invalidate these assumptions. Here again much more investigation is needed.

One must also realize that all of the above investigations for flow through a single fracture have considered only the effects of displacements caused by changes in normal stress. One need only consider a typical rock mass with its various discontinuities to realize that as the mass deforms, the fractures will be subjected to both normal and shear stresses. Though it is known that shear stresses are the cause of microcrack dilatancy [Brace et al., 1966], which in turn can cause an increase in the rock permeability [Zoback and Byerlee, 1975], there is little evidence in the literature for the effects of shear deformations on flow in fractures. How one should analyze the movement of fluid through such a rock mass as the stress field changes is a complex problem. Those who are attempting to develop mathematical models for fluid flow in such systems not only face this type of problem but also the fact that, at present, there are no reliable data to validate their models.

Need for Laboratory Investigations

In view of the above, the problems of size effect and the applicability of the cubic law to flow in deformable fractures will require some very careful laboratory investigations. One part of the problem is to be able to work with rock samples large enough to permit detailed observation of the flow phenomena along a fracture surface. Distribution of hydraulic pressures and a determination of flow lines are fundamental considerations. Another part of the problem is to be able to measure: (a) the actual distribution of effective stress and its relation to the asperities that are in contact, and (b) the way in which the closed regions control the effective cross-sectional areas of flow. One must ultimately be able to understand how these phenomena are affected by both normal and shear displacements. The effects of temperature changes must also be considered which will mean evaluating the role of thermal expansivity and its contribution to the displacement field.

The investigations that are envisioned will only be possible on rock samples that are much larger than the conventional size. Samples with dimensions of a meter or more will make it possible to instrument the fracture surfaces to acquire the data needed in developing the detailed understanding outlined above. Watkins (1981) discusses the problems of working with rock cores of this size and the manner in which detailed instrumental arrangements are possible. Only in this way will we be able to investigate phenomena within a fracture that is closing under an increasing state of stress and the manner in which the fracture roughness controls the flow of fluids.

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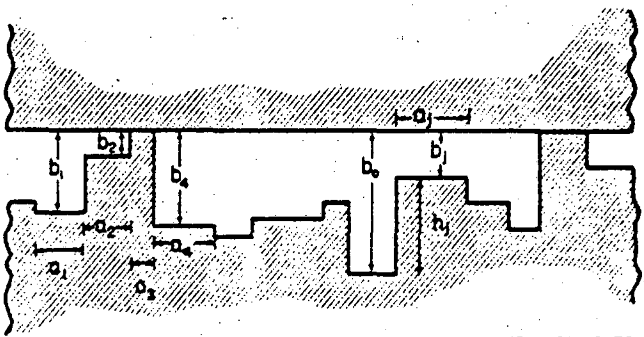

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Fig. 1. Conceptual view of roughness as an array of asperities. The two highest asperities are in contact as the fracture begins to close forming the initial aperture. Further normal displacement will cause other asperities to touch thus creating new void profiles and smaller apertures.

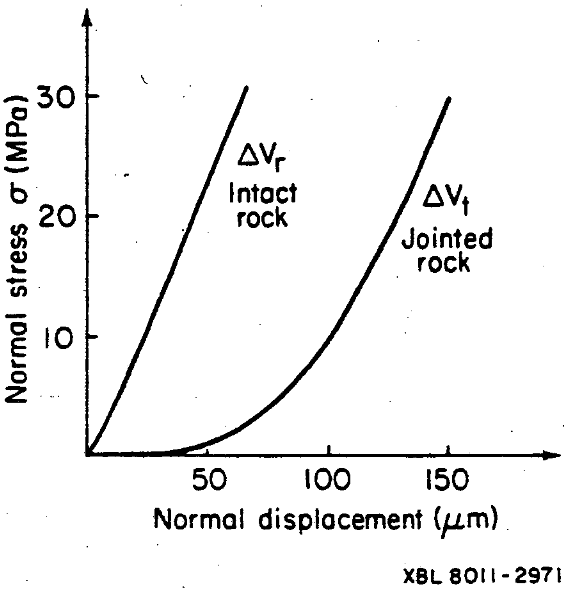

Fig. 2. Mechanical properties of intact and jointed rock showing highly non-linear behavior of jointed rock caused by the presence of a discontinuity.

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720