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Role of fluid injection in the evolution of fractured reservoirs

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ABSTRACT

A survey is provided of some of the better known examples of quantitative results during fluid injection on number, quality, and weakening effects for fractures in earth reservoirs along with some comparisons to either well-known or better-known theories of both fracture arrival and/or new growth of existing fractures through both fluid injection and stress application. The detailed analyses presented focus on reservoirs having (at worst) orthotropic symmetry.

1. Introduction

The following discussion is intended to highlight various aspects of fracture analysis as it may be applied to problems in the earth sciences, and particularly in those cases where fluids (water, gas, oil, brine, CO_2, etc.) may be involved. Certainly the importance of understanding how fluids effect the overall mechanical properties when they may be present in existing fractures in such systems is well-known, and of considerable practical importance. The additional role that fluids may play in affecting the overall behavior of these systems while being injected into existing fractures, or their role in either expanding or contracting such existing fractures, or creating new fractures is our main focus throughout.

2. Some measures of scientific and/or engineering significance

Many papers will be presented briefly in the following sections. It therefore seems both necessary and useful to comment briefly on how we might choose to grade or order the many papers discussed here. One popular method of doing so is to consider the number of times each paper has been cited in the literature by others. To account for this measure, the author has researched the citation histories of all the published papers being cited in this paper. However, it is still not clear how these data might be best presented. Should we show the raw numbers for the citations as of the writing of the present paper? Or should there be some normalization by the number of years since the publication of each paper? And how should very recent papers to treated, since they may have either no citations or very few citations as of the time of writing of the present work? The author has chosen NOT to normalize the paper citations by age, but rather to simply quote the numbers in cases where the papers have been in print long enough to accumulate some significant number of citations. In the case of the various newer papers, it was decided that all papers having at least 20 citations or more would have these numbers listed after the paper reference in the following bibliography. For papers with fewer than 20 citations as of the writing of the present paper, the resulting typically rather small number of citations is not being listed here.

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3. Early theories and analyses of fractured systems

Perhaps the earliest attempt to analyze the mechanics of fracture in solids was due to Griffith (1924). His work provides a wide-ranging discussion of fracture of various materials. His main example was glass rods, but he also discusses cracked plates, fibers, along with a brief treatment of applications to liquids. Sack (1946) (on page 730) corrects some mathematical errors in Griffith's paper, especially for materials containing circular cracks, and considers materials containing circular cracks. Sack's results may depend on Poisson's ratio of the material, whereas Griffith's results generally do not. Elliott (1947) generalized Griffith's approach for applications to metals, and provides a discussion of cracks in both 2D and 3D. This work concentrates especially on penny-shaped cracks and Griffith cracks. Results are in agreement with the experimental results of Griffith, but several differing versions of the formulas are also examined. Orowan (1949) presents an extensive review of the Griffith theory, a rederivation of those results based on atomic considerations, and also a detailed discussion about brittle strength of polycrystalline aggregates. However, the work of Brace (1960), which generalizes Griffith's approach and applies it to rocks, is one good example of work more pertinent to our present goals. Rice (1968) points out that the Griffith theory of elastic brittle fracture is also mathematically identical to the theory of fracture based on atomic cohesive forces as presented by Barenblatt (1962).

The works of Dugdale (1960) and Barenblatt (1962) are not themselves so directly pertinent to our targeted earth sciences problems, but they are nevertheless mentioned frequently in the references in later works by Rice (1968), Broberg (1971) and others, and therefore provide useful background for various related fracture analyses and applications.

Another early paper, and one that will play a major role in the later analyses of fluid effects here, is due to Athy (1930). This paper is the earliest one known to the author that introduces a nonlinear (or exponential) dependence into the formulas for mechanical behavior (i.e., elastic deformation) of soils. In particular, Athy shows that

$$D = B + A(1 - e^{-bx}), \tag{1}$$

where D is the density of the soil, B is 1.4 – which is the density of a surface clay, A is 1.3 – which is the maximum density of increase possible, b is a constant, and x is the depth of burial.

Brace (1960) provides useful information about early applications of Griffith's ideas (originally emphasizing applications to glass – but Griffith's discussion is more wide ranging than that) when applied to rocks. There is also a related preprint available online by Brace on the same topic, having the title: "Dependence of fracture strength of rocks on grain size."

Warren and Root (1963) is one of the classic references on double porosity modeling of reservoirs. Porosity is then assumed to be of two types: the first type is called *primary porosity*, being intergranular and controlled by deposition and lithification. It is highly interconnected and typically can be correlated with the permeability. The second type is called *secondary porosity* and is controlled by fracturing, jointing, or solution in circulating water. Secondary porosity is not highly interconnected, and therefore usually not correlated very well with the system permeability. They introduce the now well-known "sugar-cube model" with the matrix (being the primary regions containing porosity) composed of the cubes, and thin rough regions between these cubes being the locations of the fractures.

Broberg (1971) gives an extensive discussion of stable and unstable crack growth in several areas of application, but mostly treats sheets of PVC, and metals. He quotes the Dugdale crack model extensively, and also the J integral for crack applications due to Rice. His work compares and contrasts those results with the results of the Griffith energy approach to crack modeling.

Nilsson (1973) emphasizes the fact that Rice's J-integral formulas are limited to static cases. So the work of Rice (1971), Broberg (1971), and others involving the J-integral cannot be applied directly in cases that involve dynamics, only statics and quasi-statics. However, he also shows how to modify these earlier analyses in order to include inertia effects in order to make the problems more realistic for a wider range of applications.

White (1973) provides an efficient method of defining the failure surface in a numerical modeling code. He develops a systematic way of classifying and presenting material failure data for earth media that are approximately isotropic on the average. His functional is defined by

$$I_{2D}^{1/2}(f) = A_1(I_1) + A_2(I_1)I_{3D}{}^{1/3} + A_3(I_1)I_{3D}{}^{2/3}, \tag{2}$$

where

$$I_1 = -(\sigma_1 + \sigma_2 + \sigma_3), \tag{3}$$

which is three times the pressure.

$$S_i = \sigma_i - \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3), \tag{4}$$

for $i = 1, 2, 3$.

$$I_{2D}^{1/2} = +\{(1/2)[(S_1)^2 + (S_2)^2 + (S_3)^2]\}^{1/2}, \tag{5}$$

$$I_{3D}^{1/2} = (S_1 \cdot S_2 \cdot S_3)^{1/3}. \tag{6}$$

The more recent work by Rubin (1991) is based in part on White's paper.