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Conductivity of narrow fractures filled with a proppant monolayer

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ABSTRACT

A simplified approach for calculating the conductivity of narrow fractures filled with a sparse monolayer of proppant particles is developed. The proppant particles are modelled as rigid spheres and the deformation of the fracture faces is assumed to be purely elastic. Hertz contact theory and the principle of superposition are utilised to obtain the fracture opening profile as a function of the proppant concentration and the value of confining stress. The conductivity of the deformed fracture channel is determined by using computational fluid dynamics.

It has been demonstrated that some optimal proppant concentration exists, which maximises the fracture conductivity. Based on the simplified approach developed in this paper, the optimal concentration has been obtained as a function of the confining stress and the material properties of the fractured medium. The results are compared with previously published experimental data, which also indicate the existence of an optimal proppant concentration. A reasonable agreement between theoretical and experimental results is observed.

1. Introduction

The primary goal of fracture stimulation technologies is to create conductive pathways for fluid flow towards a producing well. The injection of propping agents helps in keeping the fractures open and ensuring high fracture conductivity in the presence of high confining stresses. The problem of maximizing the fracture conductivity by the use of optimal concentration of proppant has many important applications in oil/gas recovery technologies such as hydraulic fracturing (Economides and Nolte, 1989) and hydraulic stimulation of natural fractures (Kotousov et al., 2011a). The fracture flow capacity of hydraulic fractures is typically increased by filling the fracture channels with multiple layers of proppant particles referred as proppant packs. However, in many cases, such as hydraulic fracturing of gas shales and coal bed methane reservoirs, a complex network of narrow secondary fractures may be present which cannot be filled with proppant packs (Warpinski et al., 2008). In such fractures, a partial monolayer of proppant, i.e. a single layer of sparsely spread proppant particles could be used for enhancing the fracture flow capacity (Fredd et al., 2000). In order to facilitate the transport of proppant in narrow fracture channels, special low density proppants are normally utilised (Brannon et al., 2004; Schein et al., 2004; Kendrick et al., 2005).

Due to the presence of a single layer of proppant between the fracture walls, fractures with a partial proppant monolayer are much narrower and differ significantly from fractures filled with proppant packs in terms of their permeability characteristics and in their response to confining stresses. Darin and Huitt (1959) proposed that due to the open fracture space available around and between proppant particles, partial monolayers could provide similar or superior fracture conductivity in comparison with proppant packs. However, fractures with a partial proppant monolayer were also found to be more susceptible to loss in conductivity under high confining stresses. In relatively soft formations, the loss in conductivity was attributed to the embedment of proppant particles in the fractured rock (Huitt and McGlothlin, 1958). In hard formations, the loss in conductivity was explained in terms of crushing or excessive deformation of proppant particles under high confining stresses (Huitt et al., 1959).

A number of experimental studies have been conducted to determine the effect of proppant concentration and confining stresses on the fracture flow capacity. A wide variety of proppant such as Brady and Ottawa sand, sintered bauxite, ultra-lightweight proppant (UWP) as well as low density thermoplastic proppants have been tested (Fredd et al., 2000; Parker et al., 2005; Brannon and Starks II, 2008; Kassis and Sondergeld, 2010; Gaurav et al., 2012). The experimental studies have demonstrated that fracture channels filled with a partial proppant monolayer could achieve a high fracture flow capacity comparable or even higher than the traditional multiple layer placement. Another important finding was that an optimal proppant concentration exists, at

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which the flow capacity of a partial monolayer reaches maximum for a certain level of confining stress.

In the present work, a simplified theoretical approach is developed which can be used to determine the conductivity of partial monolayers in formations where the proppant deformation and crushing are negligible compared to the fracture deformation. A number of simplifications were adopted in order to allow for the theoretical modelling of the permeability enhancement mechanisms associated with the placement of proppant monolayers in fracture channels. These include a disregard of the surface roughness of fractures, possible nonlinear deformations around the contact zone between the proppant and fractured medium and possible secondary cracking of fracture walls due to very high contact stresses (Lawn, 1998). The elastic deformation of the propped fracture is considered to be the primary mechanism of fracture conductivity loss in this paper. These assumptions impose rather strict limitations on the application of the developed approach to accurately predict the conductivity of fracture with partial monolayers. However, the conducted study can be useful to provide insight into the mechanisms controlling the fracture flow capacity as well as to provide rough estimates of the optimum proppant concentration. In the next section, the mathematical model used to obtain the deformed shape or opening profile of the fracture is described.

2. Elastic deformation of the propped fracture

A fracture filled with a partial monolayer of proppant particles and subject to confining stresses can modelled as an array of rigid spheres squeezed between two semi-infinite elastic bodies. The problem of determining the fracture opening profile can be simplified by considering a regular arrangement of these rigid spheres. For a regular arrangement of particles, the opening profile of the fracture would vary periodically such that it is equal to the particle diameter at the points of contact and reduces to some intermediate value between the particles. To obtain such an opening profile, the following contact problem is formulated.

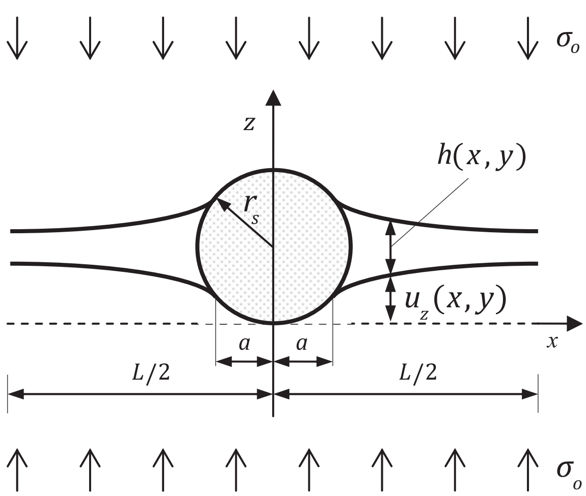

Fig. 1. Problem geometry and coordinate system.

The elastic spaces are subjected to remote compressive (confining) stresses, σ_o as illustrated in Fig. 1. The spheres are arranged in a square array such that the distance between adjacent spheres is equal to L. For such an arrangement, the symmetry element or repeating unit is given by the region $-L/2 \leq x,\ y \leq L/2$, with a particle of radius r_s at its centre i.e., $(x,y)=(0,0)$. The fracture opening profile is denoted by $h(x,y)$. As a result of elastic deformation, the opening of the fracture h decreases with increasing distance from the particles and the minimum opening h_o occurs at the corners of the symmetry element i.e. at $(x,y)=(\pm L/2,L/2),(\pm L/2,-L/2)$. The opening profile is periodic such that $h(x+L,y)=h(x,y)=h(x,y+L)$.

The contact problem is decomposed into: the indentation of an elastic half space by rigid spheres and a uniform pressure applied on the surface of an elastic half space, as shown in Fig. 2. Solutions to these problems based on Hertz contact theory are readily available from the literature (Johnson, 1985; Fischer-Cripps, 2007 among others). The effect of neighbouring spheres on the fracture deformation can be found by using the principle of superposition and utilising the Saint-Venant principle. When the contact zone size is relatively small in comparison with the characteristic length of the problem L, the changes of the contact zone and redistribution of the contact pressure due to the particle interactions are small and they can be neglected (Kotousov, 2011b).

For the problem of indentation of an elastic half space by a rigid sphere (Fig. 2a), the indentation load P acting on the sphere is equal to $\sigma_o L^2$, where L^2 is the area of the symmetry element. The radius a of the contact zone between the sphere and the elastic half plane can be calculated by using the following relationship (Fischer-Cripps, 2007):

$$a^3 = \frac{3}{4}\frac{(1-v^2)\sigma_o}{E} r_s L^2 \tag{1}$$

where σ_o is the remote confining stress, E is the modulus of elasticity and v is the Poisson ratio of the rock material. The vertical displacement of the surface of the elastic half-space at a distance r from the point of contact can be written as

$$u_o(r) = -\frac{(2a^2-r^2)}{2r_s}, \quad r \leq a \tag{2a}$$

$$u_o(r) = -\frac{1}{\pi r_s}\left[(2a^2-r^2)\sin^{-1}\frac{a}{r} + r^2\frac{a}{r}\left(1-\frac{a^2}{r^2}\right)^{1/2}\right], \quad r \geq a \tag{2b}$$

The cumulative displacement $u_1(x,y)$ due to the array of spheres at any point within the symmetry element $-L/2 \leq x,y \leq L/2$ can be obtained by using the principle of superposition. As shown in Fig. 3, we consider a boundary of radius R around the element of symmetry and incorporate the effect of neighbouring spheres lying within this

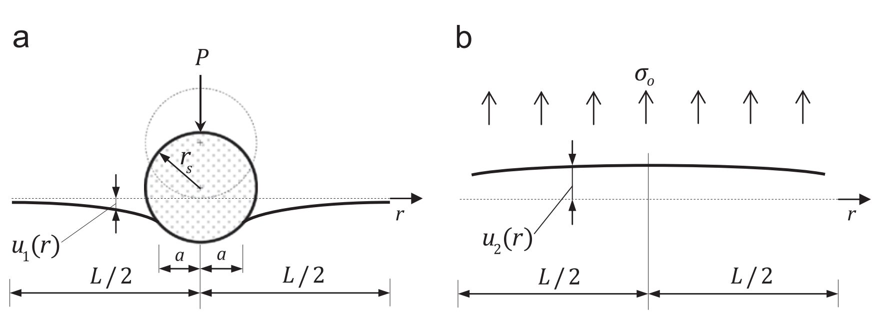

Fig. 2. Decomposition of the contact problem.