International Journal of Rock Mechanics & Mining Sciences 95 (2017) 48–61

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Fracture mechanics approximation to predict the breakdown pressure using the theory of critical distances

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ARTICLE INFO

Keywords:
Hydraulic fracturing
Breakdown pressure
Critical distance
Fracture mechanics

ABSTRACT

The breakdown pressure is an important parameter that influences the hydraulic fracturing process of the rock. This paper presents a new approach for the prediction of the breakdown pressure in hydraulic fracturing based on the theory of critical distances. The proposed method of analysis assumes that a pressurized crack is formed at a critical distance into the material prior to the unstable propagation. The breakdown pressure is calculated using an analytical approximation of the mode I stress intensity factor for this pressurized crack. A series of hydraulic fracturing experiments were conducted and the test results were compared with those predicted from the proposed method of analysis. The approximation aligns with these test results as well as with published results from independent hydraulic fracturing experiments.

1. Introduction

Hydraulic fracturing is a mechanical process whereby pressurized fluid causes unstable fracture propagations into a rock mass. These generated fractures alter the properties of the rock mass, including its permeability, strength, and anisotropy. Hydraulic fracturing can occur by natural processes. However, since the early 1950s this mechanical process has been utilized by the hydrocarbon extraction, geothermal, mining and other related industries to take advantage of these altered rock mass properties.[1] Specifically, enhanced geothermal systems and unconventional gas reservoirs rely on hydraulic fracturing to increase the permeability of the reservoir by producing new fractures and/or stimulating pre-existing discontinuities. In such systems, fractures act as main fluid/gas conduits and heat exchange surfaces.

In addition, hydraulic fracturing can be used for rock stress estimation. The apparatus needed for this in-situ stress estimation in the field requires; surface equipment, straddle packer, high-pressure tubing, drill pipe, or hose, pressure gages, pressure transducers and a flow meter, pressure generators and recording equipment. One item of note is the straddle packer, which seals the borehole test interval. The straddle packer is two inflatable rubber packers, spaced apart at a distance equal to at least six times the borehole diameter. These two packers are connected mechanically as well as hydraulically to create one unit (i.e. the straddle packer).[2] This specified distance between the two inflatable rubber packers is used for rock stress estimation. However, this chosen length is arbitrary for those hydraulic fracturing operations that do not choose to estimate the rock stress conditions. Therefore, there are two different predominate features of the hydraulic fracturing experiments performed in this study compared to hydraulic fracturing tests for rock stress estimation; this pressurization length is small compared with the diameter of the borehole, and stainless steel tubing attached to the borehole wall via epoxy is used to mimic the straddle packer.

To locate the effective hydraulic fracturing treatment zones and create an optimal operational fracture network within the rock mass, it is important to predict the maximum internal pressure that the material can withstand, i.e. the breakdown pressure. This breakdown pressure is an important initial parameter that affects the fracturing of the rock mass and hence the enhanced permeability of the system. However, the fracturing process is complex as it depends on various factors including the injection rate, fluid properties, borehole radius, in-situ stress condition, and the rock (mass) properties. Currently there are several theories developed for the prediction of breakdown pressures with varying degrees of success,[3–5] but this remains an active research area in hydraulic fracturing.

The in-situ stress condition of the rock mass is one factor that influences the breakdown pressures of an intact material. Generally, one remote compressive principal stress direction is defined (and assumed) as vertical; therefore, the other two remote principal stresses are horizontal, by definition. The vertical and horizontal compressive principal stress magnitudes can be different therefore, they are denoted the vertical principal stress σ_v, the minor horizontal principal stress σ_h, and the major horizontal principal stress σ_H. These remote compressive principal stresses in the rock mass are disturbed by the presence of the

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http://dx.doi.org/10.1016/j.ijrmms.2017.03.006
Received 20 July 2016; Received in revised form 16 February 2017; Accepted 9 March 2017

borehole and the pressurized fluid. This perturbed stress field near the borehole is usually utilized to estimate the breakdown pressure expected. It is suggested, that this concept may be used for an undamaged rock; however, if the material forms any crack or cracks, the elastic spatial stress tensor for a pressurized borehole will not be valid. The elastic spatial stress tensor can be used to estimate the onset of crack initiation. However, once a crack forms, it is suggested that this damaging process must be taken into account when considering the breakdown pressure. The damage process during hydraulic fracturing will cause a fracture to form perpendicular to the minor principal stress direction (or the lowest principal stress direction). Although, the presence of cracks may cause the spatial stress field to be different compared with pressurized intact rock using fluid pressure in a section of borehole; this concept of an intact (undamaged) rock is commonly used.

Therefore, one of the most frequently adapted theories, to estimate the breakdown pressure, uses this elastic spatial stress tensor for a pressurized borehole.[6,7] This model calculates the breakdown pressure P_f, for a vertical borehole associated with producing a vertically orientated fracture in a normal faulting stress regime ($\sigma_v \geq \sigma_H \geq \sigma_h$) by the following [8]:

$$P_f = \sigma_t + 3\sigma_h - \sigma_H \tag{1}$$

where σ_t is the tensile strength of the rock, σ_h and σ_H are the remote minor and major horizontal stresses, respectively. For this simplified case of the borehole axis aligned vertically, the tangential stress on the wall of the borehole is not affected by the remote vertical principal stress σ_v, as illustrated in Eq. (1). Therefore, only for these conditions and using this theory, the principal stress σ_v, is not considered to influence the breakdown pressure of a vertical borehole. When the in situ pore pressure is considered, Eq. (1) becomes:

$$P_f = \sigma_t + 3\sigma_h - \sigma_H - p_0 \tag{2}$$

This conventional model predicts the failure of the rock to take place on the walls of the pressurized borehole. However, when the apparent tensile strength is back calculated using this expression, the value is found to be greater than that measured directly from tensile strength tests.[9] In addition, this theory cannot account for the reduction in breakdown pressure when the borehole diameter is increased.[3]

Ito and Hayashi[3] and Ito[10] introduced a theory to predict the initiation of a fracture due to hydraulic pressure where they assumed the initiation occurs when the maximum effective tensile stress reaches the tensile strength of the rock at a critical distance into the rock. (See Fig. 1 for a graphical representation of the difference between initiation pressure and breakdown pressure).

Therefore, by definition, this initiation pressure is lower than the breakdown pressure. The degree of non-linear behavior in the pressure versus time or cumulative volume near the peak stress determines the closeness of the initiation pressure with the breakdown pressure. If there is a substantial amount of non-linear behavior, the initiation pressure may differ significantly to the breakdown pressure. Haimson and Fairhurst[4] derived an equation to convert between the initiation pressure and the breakdown pressure:

$$P_f = \left[2 - \alpha\left(\frac{1-2\nu}{1-\nu}\right)\right]P_i \tag{3}$$

where α is Biot's poro-elastic parameter, and ν is Poisson's ratio. Biot's parameter ranges between 0 and 1, and is calculated by the following expression[11]:

$$\alpha = 1 - \frac{C_r}{C_b} \tag{4}$$

where C_r is the material matrix compressibility and C_b is the material bulk compressibility. For a more detailed review of poroelasticity for rocks, refer to Jaeger et al.[12]

Ito[10] predicts lower and upper bound values for the initiation pressure. They express this upper limit as the following, corresponding to very high injection rate:

$$P_i = \left(1 + \frac{a_{Ic}}{R}\right)^2 \left\{\sigma_t - \left[\frac{\sigma_H + \sigma_h}{2}\left(1 + \frac{R^2}{(R + a_{Ic})^2}\right) - \frac{\sigma_H - \sigma_h}{2}\left(1 + 3\frac{R^4}{(R + a_{Ic})^4}\right)\right]\right\} \tag{5}$$

In addition, they define the lower limit as the subsequent expression, corresponding to a very slow injection rate:

$$P_i = \frac{\sigma_t - \left[\frac{\sigma_H + \sigma_h}{2}\left(1 + \frac{R^2}{(R + a_{Ic})^2}\right) - \frac{\sigma_H - \sigma_h}{2}\left(1 + \frac{3R^4}{(R + a_{Ic})^4}\right)\right]}{\left(1 - \frac{\alpha}{2}\right)\left\{1 + \frac{1}{(1 + a_{Ic}/R)^2}\right\}} \tag{6}$$

where R is the borehole radius and a_{Ic} is the critical distance. A numerical approach is needed to derive the predicted initiation pressures between these ranges, based on the pressurization rate of the experiment.

In this current study, the theory developed by Ito and Hayashi[3] and Ito[10] is extended to overcome the limitation that the previous theory predicts the initiation pressure but not the breakdown pressure directly. An analytical expression is derived using the method described in this paper and the lower and upper bound analytical expressions from Ito[10] are used to compare the results. Hydraulic fracturing experiments were also performed and evaluated by the derived analytical expression. The close alignment of the derived expression to experimental results highlights its significance. Note our experiments were conducted under constant flow rate, whereby the pressurization rate is not constant.

In addition, it has been hypothesized in other experimental studies that before the breakdown pressure is reached, a stable crack develops.[8,13] For example, there was evidence presented that the borehole breakdown occurred when the initiated fracture became unstable after a significant growth[13] (with 7.6–76.2 mm in length). Therefore, this observation of a stable crack is used as a concept in this study. In addition, this assumed stable crack is formed perpendicular to the minor principal stress direction, which is consistent to the findings in an experimental study by Hubbert and Willis.[14] To further support the current analysis, it has been found through statistical analysis of their experimental results that breakdown pressures have a stronger relationship with the magnitude of the associated minor principal stress compared with the tensile stress at the wall of the borehole.[5] It has been shown that the theory of critical distances[15] can predict accurately the tensile failure (the maximum stress) of brittle material with notches of various sizes.

It is notable that for different rock types the critical distance values vary significantly from each other. For example, even for the same rock type (andesite) in the study by Ito and Hayashi,[3] the critical distance ranges from 1.54 mm for Honkomatsu andesite to 3.39 mm for Kofu

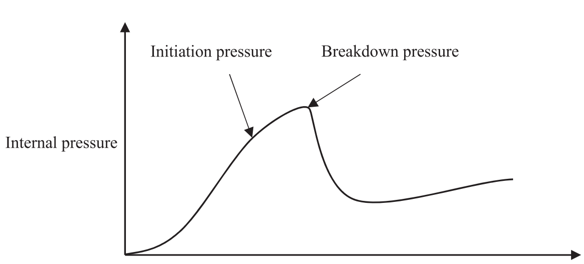

Fig. 1. Conceptual internal pressure versus time graph, indicating the difference between initiation pressure and breakdown pressure.