Journal of Rock Mechanics and Geotechnical Engineering xxx (2018) 1–10

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Propagation and aperture of staged hydraulic fractures in unconventional resources in toughness-dominated regimes

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ARTICLE INFO

Article history:
Received 10 June 2017
Received in revised form
15 August 2017
Accepted 29 August 2017
Available online xxx

Keywords:
Hydraulic fracturing
Stress intensity factor (SIF)
Aperture
Numerical analysis
Gas shale

ABSTRACT

Simultaneous multistage hydraulic fracturing of unconventional gas shale in parallel multilateral wells is an effective technique to raise the connectivity of the reservoir to the wellbore and improve reservoir permeability for an economical production. However, this technique should be accompanied with some optimization procedures to obtain an efficiently fractured reservoir with the highest production and the lowest cost. In unconventional hydraulic fracturing, fracture deviation/collapse and trapping are familiar phenomena which occur when a non-optimized fracturing pattern is used. These problems occur respectively when stress shadow size has not been considered in optimization and fracturing pressure is higher than the available pressure in the sealed section. Therefore, in an optimized hydraulic fracturing, having straight fractures with no deviation or collapse needs consideration of stress shadow effect (SSE). Apart from that, having efficiently propagated fractures to the extent of the reservoir without any fracture trap requires consideration of stress intensity factor (SIF) and aperture. SSE was studied and published by the authors in 2014. For the case of SIF, investigating any change in mode I SIF and aperture with different influencing variables such as fracture geometry and pattern are studied in the current research work. Three different fracturing techniques are assumed as multistage fracturing, simultaneous single-stage fracturing, and simultaneous multistage fracturing techniques. Since obtaining SIF for three-dimensional fractures is a challenging issue, a stress ratio technique is used for calculation of SIF ratios of different fracturing scenarios compared to the case of a single fracture. Therefore, changes of SIF for different fracturing schemes are estimated and analyzed to understand whether or not a fracturing scheme is efficient and all the spaced perforations are activated and change to hydraulic fractures.

1. Introduction

Unconventional reservoirs have received more attentions in recent years due to the declining productivity of conventional reservoirs. In 2009, almost 50% of domestic US gas production was attributed to unconventional resources and it is estimated to increase to almost 75% by 2035 (EIA, 2011). The permeability of these shale reservoirs, however, typically ranges from a few to about one hundred nano-darcys causing productivity from traditional well architecture and completion schemes to be limited and uneconomical. Soliman and Boonen (1997) proposed that "*as the formation permeability gets smaller, it would expectedly take a longer time to deplete the reservoir, and it may be necessary to create more fractures in completion stage to quickly deplete the reservoir*". Therefore, deployment of unconventional drilling and completion technology has been useful and influencing in order to produce economically from these reservoirs (Andrews et al., 2009). Bao et al. (2017) also found out the interference between adjacent fractures using a fully coupled finite element simulation.

In unconventional completion, single-stage fracture treatments evolved to multistage stimulation treatments and fracturing of standalone wells was progressed to simultaneous fracturing of multilateral wells in order to increase reserves per well, enhance well productivity, and improve project economics (King et al., 2008). Some researchers mentioned that an optimization is required for such completion techniques. For example, it was

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

https://doi.org/10.1016/j.jrmge.2017.08.003
1674-7755

reported that increase in spacing between the fractures induces less interference between propagating fractures and hence requires less breakdown pressure to initiate a fracture (Singh and Miskimins, 2010). In addition, no deviation or collapse of hydraulic fractures occurs under this circumstance. It is the reason of considering stress shadow concept in designing of hydraulic fracturing pattern for this kind of reservoirs. Stress shadow concept has been discussed by many researchers (e.g. Roussel and Sharma, 2011; Morrill and Miskimins, 2012; Taghichian et al., 2014).

The main purpose of hydraulic fracturing in unconventional reservoirs is to create parallel hydraulic fractures perpendicular to the horizontal wellbore and make a connected reservoir to the wellbore. In order to reach this goal, observing whether a hydraulic fracture propagates or is trapped is of paramount importance. In addition, the direction of propagation of hydraulic fractures plays a decisive role in having ideal straight hydraulic fractures with no deviation and collapse. Therefore, a fracturing pattern should be designed in such a way that simultaneously satisfies both of the above-mentioned conditions, i.e. reasonable fracturing pressure (via stress intensity factor (SIF)) and controlling the fracturing direction (via stress shadow effect (SSE)).

Propagation of hydraulic fractures depends on stress field around the tip. Hence, many researchers have tried to calculate the stress field around cracks which is influenced by crack geometry, fracturing scheme, and applied boundary conditions. In order to simplify the stress calculation close to the tip, a new term called SIF was defined. The generalized form of stress field equation for modes I, II and III of loading, valid in the vicinity of the crack tip, is given by

$$\sigma_{ij} = \frac{K_{\mathrm{I}}}{\sqrt{2\pi r}} f_{ij}(\theta) + \frac{K_{\mathrm{II}}}{\sqrt{2\pi r}} g_{ij}(\theta) + \frac{K_{\mathrm{III}}}{\sqrt{2\pi r}} h_{ij}(\theta) + \ldots \tag{1}$$

where σ_{ij} is the stress in the vicinity of the crack tip; f, g and h are the trigonometric functions; r and θ are the cylindrical coordinate components; and K_{I}, K_{II} and K_{III} are the modes I, II and III SIFs, respectively. The concept of SIF was first proposed by Irwin (1957), by which the effects of geometry and boundary conditions are separated from spatial location of stress analysis.

Assuming a planar crack in the x–z plane, one can have the SIFs as

$$K_{\mathrm{I}} = \lim_{r\to 0}\left[\sqrt{2\pi r}\,\sigma_{yy}(r,0)\right] \tag{2a}$$

$$K_{\mathrm{II}} = \lim_{r\to 0}\left[\sqrt{2\pi r}\,\sigma_{yx}(r,0)\right] \tag{2b}$$

$$K_{\mathrm{III}} = \lim_{r\to 0}\left[\sqrt{2\pi r}\,\sigma_{yz}(r,0)\right] \tag{2c}$$

One conspicuous point herein is the dependence of K_{II} and K_{III} on the shear stresses. When crack propagating, the angle of propagation in two dimensions depends on K_{I} and K_{II} which can be obtained via the following relationship (Stone and Babuska, 1998):

$$\Theta(K_{\mathrm{I}},K_{\mathrm{II}}) = \begin{cases} 0 & (K_{\mathrm{II}}=0) \\ 2\tan^{-1}\left\{\left[\dfrac{K_{\mathrm{I}}}{K_{\mathrm{II}}} - \mathrm{sgn}(K_{\mathrm{II}})\sqrt{\left(\dfrac{K_{\mathrm{I}}}{K_{\mathrm{II}}}\right)^2+8}\right]\Big/ 4\right\} & (K_{\mathrm{II}}\neq 0)\end{cases} \tag{3}$$

where Θ is the change angle of propagation direction. It is induced from Eq. (3) that no change in the propagation direction is observed in case of having no K_{II}, which corresponds with the case of having no shear stress at the tip (see Eq. (2b)). Therefore, it can be induced that having straight hydraulic fractures with no deviation or collapse needs negligible shear stresses at the tip. It is noted that this is an ideal condition which is assumed for the current analyses in order to obtain the ideal distance between hydraulic fractures propagating merely under the circumstance of mode I. Therefore, under the above-mentioned condition, the only required term to determine stress field around the crack tip is K_{I}, which changes with geometries of the crack, medium, boundary and loading conditions (Broek, 1982).

In this way, having the SIF behavior of hydraulic fractures, one can judge how/when a hydraulic fracture propagates in the medium. Many two-dimensional (2D) crack geometries have been analytically solved and their SIFs have been reported in the literature (e.g. Tada et al., 2000). However, there have also been some problems in which the geometries of cracks/medium were challenging and stress field for these fractures was not easy to be analytically determined. The SIF of such problems was defined by utilizing boundary element (BE) and finite element (FE) methods (e.g. Sih, 1973; Murakami, 1987; Tada et al., 2000). Three-dimensional (3D) cracks with different geometries, such as embedded cracks in an infinitely extended homogeneous, isotropic solid medium, opened up due to prescribed internal pressure, have also been analytically solved by a number of investigators (e.g. Keer, 1964; Sneddon and Lowengrub, 1969; Shah and Kobayashi, 1971; Guidera and Lardner, 1975). Mastrojannis et al. (1979) also developed a method for determination of SIF for a general-shaped crack with internal pressure in an infinite medium utilizing numerical integration. Furthermore, using the 2D Fourier transform method, Kassir (1981) succeeded in solving the SIFs around rectangular cracks. Nejati et al. (2015) also proposed a novel domain integral approach for SIF calculation of 3D cracks with tetrahedral elements and not requiring any structured mesh. It is worth mentioning that SIF of 3D cracks depends on spatial location around the crack edge. For instance, for an internally pressurized rectangular crack, SIF along the length is higher than that along the width. According to Kassir and Sih (1966), a basic characteristic of any 3D crack problem is the fact that the state of stress in a normal plane near a smooth crack front is essentially a plane-strain one. Therefore, for a rectangular crack internally pressurized, SIF is the highest along its length and it can be determined as

$$K_{\mathrm{I}} = P_{\mathrm{H}}\phi(AR)\sqrt{\pi a} \tag{4a}$$

where

$$\phi(AR) = f_1[f_2 - \exp(-f_3 AR)] \tag{4b}$$

where P_{H} is the internal pressure; a is the half-length of the fracture; AR is the fracture aspect ratio; and the coefficients f_1, f_2 and f_3 are defined as 0.5415, 1.8086 and 0.6943, respectively.

For almost all of the 3D crack problems, with respect to analytical solutions, SIFs were proposed for single fractures. Therefore, there seems to be lack of enough knowledge about the SIF values for the cases where multiple fractures exist in the medium. In hydraulic fracturing of unconventional reservoirs, due to the existence of many 3D fractures in the medium, the SIF change of multiple fractures placed between parallel lateral wells should be studied. Any fracturing scenario having a higher ratio of SIF with respect to the case of a single fracture in a standalone well can be considered as a fracturing technique with higher propagation potential in the target zone. Study of SIF behavior for different fracturing scenarios can be considered as a simultaneous tool required for optimization of hydraulic fractures together with SSE.

Please cite this article in press as: Taghichian A, et al., Propagation and aperture of staged hydraulic fractures in unconventional resources in toughness-dominated regimes, Journal of Rock Mechanics and Geotechnical Engineering (2018), https://doi.org/10.1016/j.jrmge.2017.08.003