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Investigate effects of weak bedding interfaces on fracture geometry in unconventional reservoirs

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ABSTRACT

Shale formations often consist of multiple weak interfaces between layers, which is easily opened during hydraulic fracturing treatment and affect growth of fracture height. Fracture propagation in such formations usually induced complex fracture geometry with primary vertical fractures and horizontal fracture segments between layers. Although numerous numerical models have been developed to simulate fracture propagation in unconventional reservoirs, relatively few physical three-dimensional models exist to quantitatively simulate opening of fractures affected by weak interfaces. In this paper, we analyze width profile of fractures and interaction of vertical and horizontal fracture segments with predetermined fracture path under the assumption of neglecting the flow effect.

A fully three-dimensional displacement discontinuity method (3D DDM) is introduced to model multiple fractures in a stage in three dimensions. The fracture geometry is prescribed, which combined with vertical and horizontal fractures. In each case, the horizontal fracture is regarded as opening of the bedding interface and vertical fracture would either be arrested or directly cross the interface. Interfacial sliding distance, defined as width jump of the vertical fracture at the interface, is regarded as a primary impact of fracture height containment. Analysis of fracture opening, shear displacements and interfacial sliding distance is given for both vertical and horizontal fracture segments. When multiple vertical fractures intersect with a horizontal interface, shear displacements are induced on the interface and vertical fractures have smaller width compared with the case without the horizontal interface, as a result of the interaction with the interface. We observed that both widths of fracture segments and interfacial sliding distance are positively correlated with the distance between the center of the vertical fracture and the horizontal interface, half-length of horizontal fracture segment, the net pressure within fracture segments. Conversely, Young's Modulus has a negative relationship with both width of fracture segments and interfacial sliding distance. This paper analyzes the effects of opening of weak interfaces and provides critical insights of fracture width distribution and its impacts on proppant transport.

1. Introduction

Unconventional shale reservoirs have been the most recent production frontier in the United States. Optimization of the production of shale reservoirs is greatly dependent on hydraulic fracture treatment. Shale formations usually have laminated structures resulting in directionally dependent rock properties, in-situ stress states, and interface properties. Currently, numerous simulators have been developed to model fracture propagation in unconventional shale reservoirs (Bagheri and Settari, 2008; Zhang et al., 2009; Dershowitz et al., 2010; Weng et al., 2011; McClure, 2012; Xu and Wong, 2013; Wu and Olson, 2013). However, how to precisely estimate the height growth in rock formations with weak interfaces is still a big challenge. Previous study indicated that fracture height is overestimated if hydraulic fracture models merely consider the mechanisms of stress contrast (Simonson et al., 1978; Palmer and Carroll Jr., 1983; Adachi et al., 2010) and modulus contrast (Van Eekelen, 1982; Smith et al., 2001; Gu and Siebrits, 2008) between adjacent layers. Based on model predictions (Daneshy, 1978; Cooke and Underwood, 2001; Miskimins and Barree, 2003; Gu et al., 2008; Abbas et al., 2014; Chuprakov and Prioul, 2015; Liu and Valko, 2015; Cohen et al., 2017; Izadi et al., 2017), experimental investigations (Teufel and Clark, 1984; Thiercelin et al., 1987; Zhang et al., 2007; Zhang and

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Jeffrey, 2008; Bunger et al., 2015; Xing et al., 2016), and field studies (Warpinski and Teufel, 1987; Rutledge et al., 2016; Suarez-Rivera et al., 2016), they reveals that weak interfaces also play an important role in determining the fracture height growth during hydraulic fracturing treatment. Gu et al. (2008) considered the interfacial sliding between bedding layers (weak interfaces) as one of the mechanisms that would alter hydraulic fracture growth. Fisher and Warpinski (2012) indicated that weak interfaces are regarded as a significant factor in stopping fracture height growth at shallow depths, initiating interface fractures or creating offsets along the interface. Laboratory investigation (Bunger et al., 2015) showed that hydraulic fracture propagation is ceased as a result of fluid infiltration into the weak interface. Suarez-Rivera et al. (2016) illustrated that the distribution of weak interfaces is an indicator for proper selection of the lateral landing depth, which helps improve the final propped and connected fracture height and enhances the well performance. Although numerous numerical models have been developed to simulate fracture propagation in unconventional reservoirs, relatively few physical 3D models exist to quantitatively model the opening of fractures affected by weak interfaces. Rutledge et al. (2015) presented a model with step-over features to describe the sliding along the bedding interface which driven by the opening of the vertical fracture. Chuprakov and Prioul (2015) elaborated a FracT model which can solve the problem of elasto-frictional fracture contact with weak horizontal interfaces. Cohen et al. (2017) proposed a new Stacked Height Growth model (SHG), regarded as an enhanced Pseudo 3D model (P3D), can model the effect of ledges at weak interfaces. Izadi et al. (2017) developed a fully coupled 3D hydraulic fracturing simulator to investigate multiple fractures interference with consideration of the effect of bedding planes.

In this paper, a fully three-dimensional displacement discontinuity method (3D DDM) is introduced to model multiple fractures in three dimensions under the influence of weak interfaces. Compared with finite element method, 3D DDM only discretize fracture geometries, which greatly decreases the computational cost. The Displacement Discontinuity Method (DDM) was firstly introduced by Crouch (1976) for solving fracture-related problems and widely implemented in hydraulic fracture modeling to calculate rock deformation (Olson, 2004; Shen, 2014; Wu and Olson, 2015; Xie et al., 2016; Nintcheu Fata, 2016). In this paper, we analyzed fracture width profiles and interactions of vertical and horizontal fracture segments with different predetermined fracture geometries under the assumption of neglecting the flow effect. In each case, the horizontal fracture is regarded as opening of the bedding interface and vertical fractures would either be arrested or directly cross the interface. Shear displacements are induced when multiple vertical fractures contacts with the horizontal interface and a width jump on vertical fractures can be observed at the crossing position of the interface. Far field stresses were discussed in each case but not completely analyzed as a result of beyond the scope of this paper. Compared with previous models, this fully 3D DDM has the advantage of modeling the mechanical interaction between hydraulic fractures and pre-existing discontinuities such as horizontal interfaces with arbitrary angles in three-dimensional space. In addition, this model can be also used to investigate slippage of horizontal interfaces and understand the effects of the slippage on fracture height growth.

2. Methodology

A boundary element based method, named as Displacement Discontinuity Method (DDM), was developed to determine displacements and induced stresses for three-dimensional fractures with a given boundary condition (Shou, 1993). Wu (2014) elaborated a single three-dimensional vertical fracture discretized into numerous rectangular elements in an infinite elastic medium. A fully three-dimensional displacement discontinuity method (3D DDM) is further developed for simulating multiple fractures with arbitrary angles in three dimensions under the influence of weak interfaces. An analytical solution for displacement components and stress components induced by an element with constant displacement discontinuities is shown as below (Salamon, 1964; Crouch and Starfield, 1983; Shou et al., 1997):

$$
\begin{aligned}
s_1 &= D_I\left[(1-\upsilon)T_{,3} - \frac{x_3}{2}T_{,11}\right] - D_{II}\left[\frac{x_3}{2}T_{,12}\right] - D_{III}\left[\frac{(1-2\upsilon)}{2}T_{,1} + \frac{x_3}{2}T_{,13}\right] \\
s_2 &= D_I\left[-\frac{x_3}{2}T_{,12}\right] + D_{II}\left[(1-\upsilon)T_{,3} - \frac{x_3}{2}T_{,22}\right] - D_{III}\left[\frac{(1-2\upsilon)}{2}T_{,2} + \frac{x_3}{2}T_{,23}\right] \\
s_3 &= D_I\left[\frac{(1-2\upsilon)}{2}T_{,1} - \frac{x_3}{2}T_{,13}\right] + D_{II}\left[\frac{(1-2\upsilon)}{2}T_{,2} - \frac{x_3}{2}T_{,23}\right] + D_{III}\left[(1-\upsilon)T_{,3} - \frac{x_3}{2}T_{,33}\right] \\
\sigma_{11} &= G\left\{D_I[2T_{,13} - x_3T_{,111}] + D_{II}[2\upsilon T_{,23} - x_3T_{,211}] + D_{III}[T_{,33} + (1-2\upsilon)T_{,22} - x_3T_{,311}]\right\} \\
\sigma_{22} &= G\left\{D_I[2\upsilon T_{,13} - x_3T_{,122}] + D_{II}[2T_{,23} - x_3T_{,222}] + D_{III}[T_{,33} + (1-2\upsilon)T_{,11} - x_3T_{,322}]\right\} \\
\sigma_{33} &= G\left\{D_I[-x_3T_{,133}] + D_I[-x_3T_{,233}] + D_{III}[T_{,33} - x_3T_{,333}]\right\} \\
\sigma_{12} &= G\left\{D_I[(1-\upsilon)T_{,23} - x_3T_{,211}] + D_{II}[(1-\upsilon)T_{,13} - x_3T_{,122}] + D_{III}[-(1-2\upsilon)T_{,12} - x_3T_{,123}]\right\} \\
\sigma_{23} &= G\left\{D_I[-\upsilon T_{,12} - x_3T_{,123}] + D_{II}[T_{,33} + \upsilon T_{,11} - x_3T_{,322}] + D_{III}[-x_3T_{,233}]\right\} \\
\sigma_{13} &= G\left\{D_I[T_{,33} + \upsilon T_{,22} - x_3T_{,311}] + D_{II}[-\upsilon T_{,12} - x_3T_{,123}] + D_{III}[-x_3T_{,133}]\right\},
\end{aligned}
\tag{1}
$$

where G is the shear modulus and ν is the Poisson's ratio. D_I is the shear displacement discontinuity along fracture length direction, D_{II} is the shear displacement discontinuity along fracture height direction, D_{III} is the normal displacement discontinuity, also called as fracture width. T represents the derivatives of a kernel analytical solution by Green's function approach, which is represented as below:

$$
T(x_1, x_2, x_3) = \frac{1}{4\pi(1-\nu)}\int_{-b}^{b}\int_{-a}^{a}\frac{d\xi_1 d\xi_2}{\sqrt{(x_1-\xi_1)^2 + (x_2-\xi_2)^2 + x_3^2}} \tag{2}
$$

Table 1
Required parameters of vertical fracture for validation.

Parameter	Value	Unit
Vertical fracture length	2000 (609.6)	ft (m)
Vertical fracture height	100 (30.48)	ft (m)
Net pressure	1500 (1.034×10^7)	psi (Pa)
Young's modulus	3.0×10^6 (2.07×10^{10})	psi (Pa)
Poisson's ratio	0.25	