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A 3-D model for simulation of weak interface slippage for fracture height containment in shale reservoirs

Jizhou Tang, Kan Wu*

Harold Vance Department of Petroleum Engineering, Texas A&M University, College Station, TX, USA

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ABSTRACT

Shale formations often consist of multiple distinct layers with varying rock properties, in-situ stress states, and interface properties between layers. Weak horizontal interfaces often affect fracture height growth and induced complex fracture geometry. In this paper, a fully three-dimensional displacement discontinuity method is developed to investigate slippage of weak horizontal interfaces and understand the effects of the slippage on fracture height growth. Horizontal fracture segments are regarded as weak horizontal interfaces and vertical fractures would either be arrested or step over interfaces. Results indicate that a width jump of the vertical fracture occurs at the crossing position of the horizontal interface, as a result of shear displacement discontinuities along the horizontal fracture segment. The width jump hinders the vertical fracture growth in the height direction, which is regarded as a new mechanism of fracture height containment. Shear displacement discontinuities and width jump increase with the increment of the distance between the center of the vertical fracture and horizontal fracture segment. The larger the width jump, the more difficult the vertical fracture continues to propagate in the height direction, which implies that the vertical fracture tends to be arrested by the interface when the wellbore is far away from the interface.

1. Introduction

Multi-stage hydraulic fracturing in horizontal wells has been successfully employed to unlock hydrocarbon in unconventional shale reservoirs. Shale formations generally have thin beds or laminations with distinct rock properties, in-situ stress states, and interface properties between layers. Considering fracture propagation in such formations, more complicated fracture geometries with “T” shapes, kinks, and offsets are often induced (Fisher and Warpinski, 2011). Experiments (Warpinski et al., 1993) and microseismic measurements (Maxwell et al., 2002; Fisher et al., 2002) also indicate that complex fracture networks pervasively exist in unconventional reservoirs during hydraulic fracturing stimulation. Weng (2015) reviewed current available hydraulic fracturing models that deal with complex hydraulic fracture networks. In terms of modeling fracture height growth, these models face challenges due to a lack of understanding effects of weak interfaces on hindering fracture height growth.

Previous work revealed that fracture height is still overestimated if models only account for the mechanisms of in-situ stress and modulus contrast between neighboring rock formations (Van Eekelen, 1982; Palmer and Carroll Jr., 1983; Gu and Siebrits, 2008; Adachi et al., 2010). Chuprakov and Prioul (2015) stated that fracture height growth is remarkably hindered in contrast with its lateral propagation due to sedimentary laminations or beddings with thickness ranging from millimeters to meters in the vertical direction, which makes the variations of in-situ stress and rock properties in the vertical direction more significant than that in the horizontal direction. Suarez-Rivera et al. (2016) illustrated that bedding interfaces, such as bed parallel ash beds, mineralized veins, and slickensides, are regarded as a dominant factor in limiting fracture height growth in complex reservoir systems. From experimental study, Llanos et al. (2017) also demonstrated that the frictional interfaces would greatly affect the overall fracture growth due to the slip initiation along the interface. Weak horizontal interfaces play a significant role in hindering fracture height growth and generating horizontal fractures or offsets in the interfaces. However, very little work has been done to investigate the bedding layer effects on fracture geometry. Cooke and Underwood (2001) developed a numerical model to investigate fracture-interface contacting problems and analyzed frictional slip and correlated opening-mode fracture propagation using a two-dimensional Boundary Element Method (BEM). CSIRO applied a two-dimensional boundary element model to investigate the mechanisms of fluid-driven fracture intersecting with a

* Corresponding author.
E-mail address: kan.wu@tamu.edu (K. Wu).

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Nomenclature

u_j =	displacement component at a point, ft
σ_{jk} =	stress component at a point, psi
u_i =	displacement component over the boundary region, ft
t_i =	traction component, psi
K_{ij}, H_{ij}, M_{ijk}, N_{ijk} =	tensor fields with displacements at a point under a certain traction
ψ, χ =	a point location, ft
σ_{11}, σ_{22}, σ_{33}, σ_{12}, σ_{13}, σ_{23}	stress components from analytical solution, psi
x_1, x_2, x_3 =	local coordinate of the element center, ft
G =	shear modulus, psi
ν =	Poisson's ratio
$(\sigma_{SL})^i$ =	shear stress in fracture length directions at element i, psi
$(\sigma_{SH})^i$ =	shear stress in fracture height directions at element i, psi
$(\sigma_{NN})^i$ =	normal stress at element i, psi
D_{SL}^k =	shear displacement discontinuity of element k in the fracture length direction, in
D_{SH}^k =	shear displacement discontinuity of element k in the fracture height direction, in
D_{NN}^k =	normal displacement discontinuity of element k, in
J_s =	derivatives of a kernel analytical solution by Green's function approach
$A_{SL,SL}^{ik}$, $A_{SL,SH}^{ik}$, $A_{SL,NN}^{ik}$, $A_{SH,SL}^{ik}$, $A_{SH,SH}^{ik}$, $A_{SH,NN}^{ik}$, $A_{NN,SL}^{ik}$, $A_{NN,SH}^{ik}$, $A_{NN,NN}^{ik}$ =	boundary influence coefficients
$\tilde{A}_{SL,SL}^{ik}$, $\tilde{A}_{SL,SH}^{ik}$, $\tilde{A}_{SL,NN}^{ik}$, $\tilde{A}_{SH,SL}^{ik}$, $\tilde{A}_{SH,SH}^{ik}$, $\tilde{A}_{SH,NN}^{ik}$, $\tilde{A}_{NN,SL}^{ik}$, $\tilde{A}_{NN,SH}^{ik}$, $\tilde{A}_{NN,NN}^{ik}$ =	non-dimensionalized boundary influence coefficients
w =	fracture opening, ft
P =	net pressure within the crack, psi
b =	half length of the crack, ft
x =	location along the crack length, ft
$(\tilde{\sigma}_{SL})^i$ =	non-dimensional shear stress in fracture length directions at element i
$(\tilde{\sigma}_{SH})^i$ =	non-dimensional shear stress in fracture height directions at element i
$(\tilde{\sigma}_{NN})^i$ =	non-dimensional normal stress at element i
P_r =	reference net pressure, psi
$\tilde{x}, \tilde{y}, \tilde{z}$ =	non-dimensional coordinates in three dimensions
H =	reference length (fracture height), ft
$\tilde{D}_{SL}^k$ =	non-dimensional shear displacement discontinuity of element k in fracture length direction
$\tilde{D}_{SH}^k$ =	non-dimensional shear displacement discontinuity of element k in fracture height direction
$\tilde{D}_{NN}^k$ =	non-dimensional normal displacement discontinuity of element k
E =	Young's modulus, psi
L_V =	Vertical fracture length, ft
H_V =	Vertical fracture height, ft
X_H =	Horizontal fracture length in x direction, ft
Y_H =	Horizontal fracture length in y direction, ft

bedding interface and also the fluid percolation into the bedding interface (Zhang et al., 2007; Zhang and Jeffrey, 2008). Abbas et al. (2014) employed the eXtended Finite Element Method (XFEM) to study geometric effects of fracture offsets that retard fracture height growth. Chuprakov and Prioul (2015) developed an analytical model called FracT for solving the problem of elastic-frictional fracture contact with weak horizontal interfaces. Zhang et al. (2017) proposed a cell-based pseudo-3D (P3D) model considering the effect of multiple elastic layers on fracture height growth.

With the advantages of surface-only discretization and high computational efficiency, a boundary element method, Displacement Discontinuity Method (DDM), has been widely used in modeling hydraulic fracturing treatments for both homogeneous and multi-layered formations in two dimensions or three dimensions (Vandamme and Curran, 1989; Siebrits and Peirce, 2002; Wu and Olson, 2015; Kumar and Ghassemi, 2015; Kumar and Ghassemi, 2016). In this paper, we employed this method to investigate the effects of weak horizontal interfaces on fracture height growth and fracture geometry. The Two- Dimensional Displacement Discontinuity Method (2D DDM), firstly put forward by Crouch (1976), solved displacement discontinuities of fractures based on a given boundary condition. 2D DDM assumes a plane strain fracture geometry and only makes discretization along one dimension of the fracture. Olson (2004) incorporated a correction factor into 2D DDM accounting for 3D effects of the dimension without discretization. Shou (1993) developed a fully Three-Dimensional Displacement Discontinuity Method (3D DDM), regarding displacement discontinuities on each element as constants and using rectangular elements in an infinite medium. Based on 3D DDM, Wu (2014) proposed a simplified 3D DDM that only uses a single element over the fracture height and derives correction factors for 3D effects of limited height under the assumption of vertical fractures. The simplified method has a high computational efficiency as compared to the fully 3D DDM. Nintcheu Fata (2016) proposed a three-dimensional DDM scheme applying unstructured triangular meshes instead of conventional rectangular-shaped structure to conform to a domain of any shapes.

In this paper, the fully 3D DDM was developed to deal with cases of multiple fractures with arbitrary angles in 3D space. The fracture geometry, combined with vertical and horizontal fractures, is pre-determined. The cases of different fracture geometries are shown in the paper, such as a single vertical fracture, a single horizontal fracture, a crossing fracture, a T-shaped fracture, an I-shaped fracture and a complex fracture geometry with offsets. For each case, horizontal fractures can be regarded as opening of weak horizontal interfaces and vertical fractures would either be arrested or step over from interfaces. Displacement discontinuities on vertical and horizontal fractures were investigated to study the effects of opening of weak horizontal interfaces.

2. Methodology

Displacement Discontinuity Method (DDM), as a direct boundary element method, was developed to calculate displacements and induced stresses for three-dimensional fractures with a given

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