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Numerical investigation of a novel hypothesis for fracture termination and crossing, with applications to lost circulation mitigation and hydraulic fracturing

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ABSTRACT

We investigate a novel hypothesis regarding the process of hydraulic fracture termination against a preexisting frictional interface. According to current understanding, crossing occurs when small tensile fractures form ahead of the crack tip, on the other side of the frictional interface, before the concentration of stress at the crack tip causes slip along the interface. Slip blunts the concentration of stress at the crack tip and causes termination. Existing crossing criteria assume that the incipient fractures ahead of the crack tip form instantaneously once the effective stress is sufficiently tensile. However, there is a poroelastic response that causes a reduction in pressure in response to opening. This is counteracted by flow into the crack from the surrounding matrix. In very low matrix permeability formations (shale, coalbed methane, etc.), flow of fluid inward from the matrix is slow, and the opening of these incipient fractures may require a non-negligible amount of time. Using the hydro-mechanical discrete fracture network simulator CFRAC, we performed a series of numerical simulations to qualitatively investigate this process. The simulations confirm that poroelastic response could affect incipient fracture initiation and hydraulic fracture crossing. Based on this mechanism, we developed a heuristic modification to an existing crossing criterion. We applied the new criterion to investigate an injection sequence for prevention of lost circulation in fractured, low matrix permeability formations. Lost circulation occurs if wellbore fluid pressure exceeds the minimum principal stress, causing fluid loss due to propagation of a hydraulic fracture. In our proposed injection sequence: (1) injection is performed at high rate to create near wellbore fracture network complexity and then (2) viscous fluid is injected into the newly formed fractures to create resistance to flow. The simulations show that this sequence may be able to mitigate lost circulation and create a stress cage around the wellbore.

1. Introduction

1.1. Fracture crossing criteria

When a propagating hydraulic fracture intersects a preexisting fracture or plane of weakness, it may terminate against the feature, rather than propagating across. Interfaces in the subsurface often separate layers with different mechanical properties, which causes a stress contrast that results in fracture confinement (Warpinski et al., 1982; Teufel and Clark, 1984). But even in the absence of a stress contrast, planes of weakness can create mechanical interference, blunting the stress intensity at the crack tip and causing termination. Warpinski and Teufel (1987) described a hydraulic fracture mine-back experiment in which fracture termination against preexisting fractures was observed in-situ. Blanton (1982) performed experimental work on hydraulic fracture termination and found that termination was more likely with low stress anisotropy and high angle of approach (close to 90°).

Renshaw and Pollard (1995) derived an equation for predicting termination at an orthogonal intersection and validated it experimentally. Following other investigators in the literature, they assumed that crossing occurs not through continuous propagation of the hydraulic fracture tip across the interface, but rather through a discontinuous process in which a new fracture is initiated on the other side of the frictional interface (Lam and Cleary, 1984; Thiercelin et al., 1987; Helgeson and Aydin, 1991). Termination occurs when the stress ahead of the propagating hydraulic fracture is sufficient to cause slip on the interface, which blunts the crack tip. Based on these considerations, Renshaw and Pollard (1995) stated their criterion for crossing:

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Nomenclature

A	cross-sectional area of a fracture, m^2
a	fracture half-length, m
a_0	initial fracture half-length
a_e	equilibrium half-length of a crack filled with specified mass of fluid
c_f	fluid compressibility, MPa^{-1}
c_t	total compressibility, MPa^{-1}
c_ϕ	porosity compressibility, MPa^{-1}
D	cumulative sliding displacement, m
E	void aperture, m
E_0	reference void aperture, m
E_{open}	separation between fracture walls, m
e	hydraulic aperture, m
e_0	reference hydraulic aperture, m
G	shear modulus, MPa
K_I	stress intensity factor, MPa m$^{1/2}$
K_{Ic}	fracture toughness, MPa m$^{1/2}$
k	matrix permeability, m^2
L_f	hydraulic fracture length, m
L_{fi}	initial hydraulic fracture length, m
m	mass of fluid in a fracture per unit thickness, kg/m
P	fluid pressure, MPa
P_{frac}	fluid pressure in fracture
P_i	initial fluid pressure
P_0	initial fluid pressure, MPa
$q_{leakoff}$	fluid leakoff rate from fracture, kg/(s m^2)
r	distance from crack tip to frictional interface, m
r_i	initial distance from crack tip to frictional interface, m
S_0	fracture cohesion, MPa
s	source term, kg/(s m^2)
T_0	tensile strength of the rock, MPa
t	time, s
t_c	time for an opening crack to reach stress intensity factor K_{Ic}, s
v	fracture propagation velocity, m/s
η	radiation damping coefficient, MPa/(m/s)
μ	fluid viscosity, MPa s
μ_s	coefficient of friction, unitless
ρ	fluid density, kg/m^3
σ_n^r	normal stress on a fracture from remote loading, MPa
$\sigma_{n,Eref}$	90% closure stress for void aperture, m
$\sigma_{n,eref}$	90% closure stress for hydraulic aperture, m
σ_{xx}^r	compressive principal stress in the x-axis direction from remote loading, MPa
σ_{yy}^r	compressive principal stress in the y-axis direction from remote loading, MPa
σ_{yy}^r	compressive principal stress in the y-axis direction, MPa
ν	Poisson's ratio
ϕ	porosity, unitless
ϕ_{Edil}	shear dilation angle for void aperture, °
ϕ_{edil}	shear dilation angle for hydraulic aperture, °
ϕ_i	initial porosity, unitless

"Compressional crossing will occur if the magnitude of the compression acting perpendicular to the frictional interface is sufficient to prevent slip along the interface at the moment when stress ahead of the fracture tip is sufficient to initiate a fracture on the opposite side of the interface."

Their criterion states that crossing will occur if:

$$\frac{\sigma_{xx}^r}{\sigma_{yy}^r - T_0} > \frac{0.35 + \frac{0.35}{\mu_s}}{1.06}, \quad (1)$$

where μ_s is the coefficient of friction, cohesion is assumed zero, the angle of intersection is 90°, σ_{yy}^r is the remote principal stress perpendicular to the crack, σ_{xx}^r is the remote principal stress perpendicular to the interface, and T_0 is the tensile strength of the formation.

Gu and Weng (2010) extended the analytical work of Renshaw and Pollard (1995) to consider intersections of arbitrary orientation. Their work was validated experimentally by Gu et al. (2011). They found that crossing is easiest when the angle between the approaching hydraulic fracture and the preexisting fracture is 90°. When the angle of intersection is less than 45°, crossing becomes unfavorable.

Fig. 1 shows a schematic of fracture crossing, based on the concept of Renshaw and Pollard (1995) and Gu and Weng (2010). The hydraulic fracture is propagating from the left to the right, approaching a frictional interface. Ahead of the tip, tension is being induced, potentially enabling small incipient fractures to initiate at the frictional interface. These incipient fractures will enable discontinuous crossing of the interface, even after the blunting of the crack tip due to subsequent sliding of the interface. There are two overlapping regions ahead of the tip: (1) a region where stresses are high enough to cause slip on the interface, and (2) a region where stresses are high enough to induce formation of new fractures. If the slip region is larger than the region of induced fracturing, then slip will blunt the crack tip and cause termination. If the slip region is smaller than the region of induced new fractures, the Renshaw and Pollard and Gu and Weng (2010) criteria assume that the incipient fractures will form before the interface slips, enabling crossing.

Fracture crossing was investigated numerically by Thiercelin and Makkhyu (2007) and Chuprakov et al. (2011). Chuprakov et al. (2011) found that reinitiation of the new fracture may not occur directly ahead of the original hydraulic fracture, creating an offset. Chuprakov and Prioul (2015) numerically and analytically investigated how hydraulic fracture may be able to cross planes of weakness even after they have initially terminated against them, if the fluid pressure builds up sufficiently.

Beugelsdijk et al. (2000) performed experimental studies of hydraulic fracture propagation in prefractured cement blocks. They found that at high injection rate or high viscosity, a dominant hydraulic fracture formed, but at low rate or low viscosity, fluid confined to the preexisting fractures, even if fluid pressure exceeded the minimum principal stress in the block.

Hydraulic fracture termination has attracted growing interest in the field of hydraulic fracture modeling. Models have been

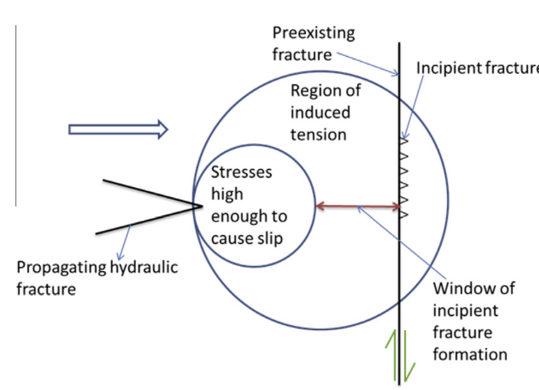

Fig. 1. Schematic of fracture reinitiation on the other side of a frictional interface.