Investigation of the Influence of Diffusion on the Closure Stress on Particles for Wellbore Strengthening Applications

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Extended Abstract

The loss of circulation is among the most important geomechanical issues in drilling engineering, as drilling fluids escape from the wellbore towards the rock formation. This event is considered a problem because it causes, non-productive time, high costs from drilling fluids losses, stuck pipe, induced kicks or in some cases loss of the entire well. Events of loss of circulation take place when the hydraulic pressure in the well exceeds (F.I.P) fracture-initiation pressure and (F.P.P) fracture-propagation pressure of the formation, a situation very common in wells with a narrow mud window. The wellbore strengthening methods are employed to increase F.I.P or F.P.P or both so as to prevent the loss circulation (Feng & Gray, 2016a,b,c; Morita & Fuh, 2012).

The fracture resistance method is employed for wellbore strengthening, in which particles that normally resemble proppants are introduced in the drilling fluid and are directed in the unwanted hydraulic fracture to act as a plug. These particles are deposited near the wellbore or at some distance inside the fracture. Of the plentiful literature it is recognised that a lack of understanding exists of the precise role of the various factors influencing the fracture propagation resistance. One of these factors is the stress change at the tip location after plugging which has proofed to be highly effective. During plugging, fluid pressure drops as the fracture is sealed thus creating a pressure difference between the fluid in the wellbore P_w and the fluid inside the fracture P_f. Poroelasticity introduces an extra pressure drop between P_f and the formation pore pressure P_p. These drops create stress change at the tip thereby causing $k_I \leq k_{Ic}$ thus providing an effective fracture resistance (Feng & Gray, 2016a,b,c; Morita & Fuh, 2012).

An open question that exists is issue of the stresses at the plug location when the closure stresses will act on the particles. In other words, the stress concentration at the plug location is ignored. In this work, we investigate whether a new fracture will be created at the plug location during wellbore strengthening operations in elastic and poroelastic formations by creating and letting a fluid driven fracture to propagate up to 5m and then plugging it for a distance of 1m. During the process, the in-situ stresses are recovered and a scaled Griffith criterion is applied to investigate the stress instabilities over the fracture path.

The coupled diffusion-deformation problem

The diffusion-deformation process is simulated by two governing equations that describe the equilibrium equation for the porous solid and the continuity equation for the fluid and the pore fluid flow which are coupled. The numerical solution of the coupled system of equations to be solved is (Sarris & Papanastasiou, 2011):

$$\mathbf{K}^{MN}\bar{c}_{\delta}^{N} - \mathbf{L}^{MP}\bar{c}_{u}^{P} = \mathbf{P}^{M} - \mathbf{I}^{M}$$
$$-\left(\mathbf{B}^{MQ}\right)^{\mathrm{T}}\bar{c}_{\delta}^{\mathrm{M}} - \Delta t\mathbf{H}^{QP}\bar{c}_{u}^{P} = \mathbf{R}^{Q}$$

where $\mathbf{R}^{Q} = \Delta t\left[-\mathbf{Q}_{t+\Delta t}^{Q} + \left(\hat{\mathbf{B}}^{MQ}\right)^{\mathrm{T}}\bar{u}_{t+\Delta t}^{M} + \hat{\mathbf{H}}^{QP}\bar{u}_{t+\Delta t}^{P}\right]$, **K** is the stiffness matrix, **L** is the coupling matrix, **P** is the external force array, **I** is the internal force array, **B** is the compressibility matrix, **H** is the flow matrix and **Q** is the nodal flow matrix. c_δ, c_u , u^M, u^P are nodal displacements and pressures with their associated shape functions. The superscripts *M*, *N*, *P*, *Q* represent the dimensions of the matrices (Sarris & Papanastasiou, 2011).

The investigation is performed numerically utilizing the FEM to obtain the hydraulic fracture solution. The solution predicts the fracture opening versus length and the propagation pressure versus length. Further to that, the stresses along the fracture plane are obtained during fracture creation and extension as well as during plugging which causes the pressure in the fracture to drop. With these stresses we apply a scaled Griffith criterion and then we compare it with the fracture toughness of the formation. The unwanted hydraulic fractures, are created by injecting an incompressible viscous fluid at a fracture inlet. Fluid flow within the fracture is modelled by lubrication theory whereas the pore fluid movement in the porous formations follows the Darcy law. The effective stresses obey the Biot poroelastic theory and the cohesive zone approach is used as the fracture propagation criterion. Furthermore, leak-off is also considered in the poroelastic case to capture the mud-cake creation at the fracture walls. The numerical models are constructed under plane strain conditions and for mode-I loading conditions hence the presented model is the well-known K.G.D (Sarris & Papanastasiou, 2011).

The following parameters have been used to investigate the fracture resistance method (Sarris & Papanastasiou, 2011; Zhou & Burbey, 2013). ***(A) Elastic rock properties***: Young modulus E = 33GPa, Poisson ratio ν = 0.26, solids density ρ_s = 880 kg/m^3 and fluid density , ρ_f = 2600 kg/m^3. ***(B) Cohesive zone properties***: Constitutive thickness = 1m, maximum traction σ_t = 7 MPa, cohesive stiffness k_n = 324 GPa, cohesive energy J_{ic} = G_{ic} = 0.112 kPa.m to map the fracture in the fracture toughness propagation regime with a fracture toughness k_{ic} = 1MPa , filter cake permeability coefficients q_t/q_b = 5.8 x 10^{-3} m/sec. ***(C) Pumping parameters***: fluid viscosity μ = 3.0 x 10^{-7} kPa.sec, injection rate q = 1.5 x 10^{-4} m^3/sec.m and rock permeability k = 2.4 x 10^{-8} m/sec. ***(D) Insitu effective stress field***: maximum insitu stress σ_{11} = 15 MPa, intermediate insitu stress σ_{33} = 13 MPa and minimum insitu stress σ_{22} = 9 MPa. ***(E) Initial conditions***: pore pressure p = 8.8 MPa and void ratio e = 0.14 [-] to represent a porosity of about φ = 12.5%.

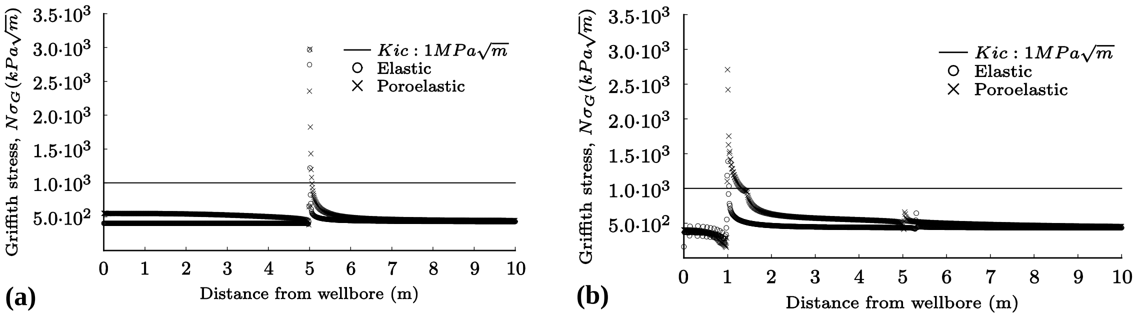

Fig. 1: Application of the Griffith criterion along the fracture propagation path [Nσ_G: Scaled Griffith stress]: (a) Normalized Griffith stress during hydraulic fracturing (fracture is at 5m), (b) Normalized Griffith stress during fall-off with fracture plug up to 5m (late times).

When the $N\sigma_G$ exceeds the fracture toughness of the material, a fracture is assumed to be created at that location. Figure (1a) shows that during propagation the $N\sigma_G$ is satisfied for a number of nodes ahead and behind the advancing fracture tip in both formations. It is also shown that the poroelastic stresses behind the advancing tip have different behavior due to the influence of pore pressure which causes diffusion effects. Figure (1b) shows the $N\sigma_G$ long after the fracture was plugged. It is evident that the $N\sigma_G$ has been significantly reduced at the tip area thus the fracture is effectively resisting propagation. However, the stresses being developed at the plug location satisfy the criterion for a new fracture that may not be of tensile nature. The poroelastic model satisfies the criterion for a number of nodes and at a distance ahead of the plug location (about 0.5 m) thus a new fracture is expected to develop. This phenomenon it appears to be amplified by the diffusion process of the fracture fluids and the pore pressure that the poroelastic model simulates.

Conclusions

With the elastic and poroelastic stress analysis performed, we have showed that the fracture effectively resists propagation and a stress instability is foreseen at the area of the plug, especially with the poroelastic model due to the diffusion process thereby compromising the structural stability of the LCM and showing that a potential risk exists for the LCM material to be released towards the well. This outlines the importance of the diffusion process for realistic predictions.

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