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Effects of in-situ stress regime and intact rock strength parameters on the hydraulic fracturing

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ABSTRACT

Crack properties and crack treatment in hydraulic fracturing process is dependent on many factors and parameters such as state of stress, rock properties, fluid properties, pump schedule, reservoir pore pressure, and many other factors. This research describes the results of numerical simulation of the hydraulic fracturing process in an oil-well using the Distinct Element Method. The numerical simulation was performed in various in-situ stress conditions with the consideration of a transient flow algorithm for fluid flow. Investigation of the effects of Young's modulus, strength parameters of intact rock (cohesion and frictional angle) and rock mass major discontinuities on the fracture properties was performed in this research. Numerical simulation showed that the fracture is initiated and propagated in the direction perpendicular to the minimum principal stress and fracture properties improve with increase in differential far-field stress. Also the calculated analysis showed that Young's modulus of intact rock plays an important role in the aperture of the created fracture and with increase in Young's modulus, the aperture of fracture will decrease. The effects of the rock mass major discontinuity on the fracture treatment showed that major geological structures would act against fracture growth and decrease the efficiency of fracturing process.

1. Introduction

Hydraulic fracturing can be broadly defined as the process by which a fracture initiates and propagates due to the hydraulic pressure applied by a fluid inside the fracture. On the application side fracturing of oil and gas reservoirs, using a mixture of viscous hydraulic fluids and sorted sand (proppant), is the most commonly used reservoir stimulation technique (Adachi et al., 2007). In this process initially the fluid is pumped into a well during a fracture treatment phase called the “prepad”. The prepad is used to fill the casing and tubing, test the system for pressure, and break down the formation. Next, the pad fluid, which is the viscous fracturing fluid used during the treatment, is pumped. No propping agent is added to the pad. The purpose of the pad is to create a tall and wide fracture that will accept the propping agent. Following the pad stage, the fluid containing the propping agent (slurry) is pumped. The slurry moves into the fracture, transporting the propping agent. The particles move up, out, and down the fracture with the slurry. The particles also can settle in the fracture as a result of gravitational forces.

In general, the main objectives of the hydraulic fracturing process are as below (Allen, 1993): (1) increasing the flow rate of oil and/or gas from low permeability reservoirs, (2) increasing the flow rate of oil and/or gas from wells that have been damaged, (3) connecting the natural fractures and/or cleats in a formation to the wellbore, (4) decreasing the pressure drop around the well to minimize sand production, (5) decreasing the pressure drop around the well to minimize problems with asphaltine and/or paraffin deposition, (6) increasing the area of drainage or the amount of formation in contact with the wellbore, and (7) connecting the full vertical extent of a reservoir to a slanted or horizontal well.

There is a rising tide of evidence from direct monitoring of actual field treatments that suggests that the fracture can grow in a complicated manner, taking advantage of local heterogeneities, layering, and natural fracture networks in the reservoir. These factors complicate the design of treatments and make numerical modeling far more challenging (Economides and Nolte, 2000).

Even in its most basic form, hydraulic fracturing is a complicated process to model, as it involves the coupling of at least three processes: (i) the mechanical deformation induced by the fluid pressure on the fracture surfaces; (ii) the flow of fluid within the fracture; and (iii) the fracture propagation.

A significant number of mathematical simulations (Lamont and Jessen, 1963; Hanson et al., 1980; Wang and Dusseault, 1991a,b) and experimental models (Blair et al., 1990; Heuze et al., 1990) have been developed to investigate the hydraulic fracturing process, but compared to the amount of research work that is

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carried out on various aspects of the hydraulic fracturing process, there are few research works that considered the interaction between fluid and rock by considering the real time for fluid flow.

In this study, an attempt has been made to assess the effects of the differential stress regimes, intact rock strength parameters and rock mass major discontinuities on the fracture treatment using the Distinct Element Method (DEM) numerical modeling techniques. In particular, numerical analyses have been carried out to investigate: (1) the effects of the far-field differential stress on the fracture orientation and its properties. (2) The effects of intact rock strength parameters on fracture properties. (3) The effects of rock mass major discontinuities on the fracturing process.

2. Modeling strategy

The numerical simulations were carried out using the distinct element method. In the distinct element method, the rock mass is represented by an assembly of discrete, deformable blocks, interacting through sets of joints, which are viewed as cohesive and frictional interfaces between distinct bodies. The blocks are considered as impermeable with flow of fluid restricted to the fractures. A fully coupled fluid-mechanical analysis is performed in which fluid flow in the fractures is dependent on mechanical deformation. The pore pressure in the fluid affects the mechanical response of the block system. The numerical method relies on the solution of the equations of motion, and mass balance for the fluid using explicit schemes.

The blocks were considered to be elasto-plastic with a Mohr–Coulomb failure criterion and a non-associated flow rule. This allowed the rock blocks to deform plastically under applied loading. The fractures were assumed to be elasto-plastic with a Coulomb slip criterion. The fractures were treated as boundary conditions between blocks, and both large displacements along fractures and rotations of blocks were allowed.

Full coupling of the mechanical and hydraulic behavior enabled the interaction between the deformation of wellbores and the hydraulic conductivity of the block system to be investigated. The fracture conductivity depends on deformation and displacement, which is in turn influenced by the fluid pressure (e.g., Pine and Cundall, 1985; Last and Harper, 1990; Lemos and Lorig, 1990; Zhang and Sanderson, 1996; Zhang et al., 1996). The fracture spaces between blocks are treated as a network of domains, each of which is assumed to be filled with fluid under pressure and in communication with its neighbors. When there is a fluid pressure differential ΔP between adjacent domains, flow will take place. The flow-rate is calculated in two different ways depending on the type of contact. For a point contact (i.e., corner-to-edge or corner-to-corner), the flow rate q is

$$q = -k_c \Delta P \tag{1}$$

where k_c is a contact permeability parameter related to the geometry of a domain.

At edge-to-edge contacts, the calculation is based on the cubic law of flow in fractures (e.g., Snow, 1968; Witherspoon et al., 1980). The flow rate is then given by:

$$q = -k_j a^3 \frac{\Delta P}{l} \tag{2}$$

where k_j is a joint permeability factor, a is the joint hydraulic aperture, and l is the contact length. In the absence of gravity, ΔP is the pressure differential between the domains. The hydraulic aperture, a is given by:

$$a = a_0 + u_n \tag{3}$$

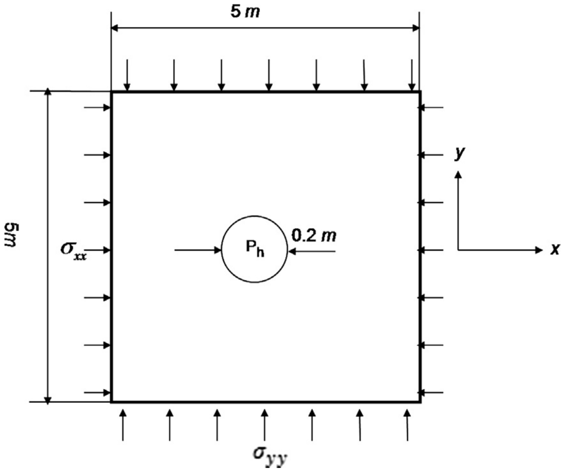

Fig. 1. Plan view of the model geometry and employed boundary conditions.

where a_0 is the aperture at zero normal effective stress and u_n is the contact normal displacement which is controlled by the normal stress and the rock properties.

At a contact location and in the normal direction, the stress–displacement relation is assumed to be linear and governed by the stiffness as below:

$$\sigma_n = -k_n \Delta u_n \quad or \quad \Delta u_n = -\frac{\sigma_n}{k_n} \tag{4}$$

The negative sign denotes that the opening is positive. Therefore, in the presence of compressive pressure, the contact aperture will decrease and under tension stress states it will increase.

A minimum aperture size a_{res} is assumed below which mechanical closure does not affect the contact permeability. Where the hydraulic pressure exceeds the normal stress acting on a fracture, it is possible to open the fracture so that the aperture is larger than a_0. Thus, a compressive effective stress will cause apertures partly to close while a zero effective stress will allow them to open to a width greater than a_0 (UDEC Theory Manual).

2.1. Model geometry

A hydrocarbon reservoir is a subsurface formation containing gas, oil, and water in varying proportions. These fluids are contained in the pore spaces of rock formations, among the grains of sandstones or in cavities of carbonates. The pore spaces are interconnected so the fluids can move through the reservoir. These porous formations have to be sealed in such a way so that the only method of escape for the fluids is through the wellbore (Baker Hughes INTEQ, 1999).

In this paper, series of 2-D models of a wellbore in a rock media are described. The analysis is focused on a two-dimensional horizontal plane strain section, perpendicular to the well axis. In plane strain conditions it is assumed that all cross-sections along a given axis (for example z-axis here) are in the same condition, and that there is no displacement along the axis. Accordingly, the strain tensor for the plane strain case can be written as below:

$$\begin{pmatrix} \varepsilon_x(x,y) & \Gamma_{xy}(x,y) & 0 \\ \Gamma_{xy}(x,y) & \varepsilon_y(x,y) & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{5}$$

For this problem the selected analysis type is valid and satisfies the problem boundary condition. In this case, we have assumed a vertical cylindrical oil well (constant cross section) and analyzed a plane strain section at the mid-height of the production well. It is assumed that the selected section is far enough from the well top