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# Model for fracture initiation and propagation pressure calculation in poorly consolidated sandstone during waterflooding

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ABSTRACT

During the process of waterflooding, the water injection pressure needs to be increased to improve the water absorption capability of formation. However, the injection pressure should be less than the fracturing pressure. Otherwise, it will cause lots of problems, such as casing failure, caprock damage and the reactivation of faults. The past works indicate that fracturing in poorly consolidated sandstone is different from fracture growth in brittle competent rocks due to strong poroelastic effect and low strength. This paper describes a new model with the consideration of fluid flow and thermal effect to calculate the fracture initiation and propagation pressure. The fracture initiation and propagation criterion for poorly consolidated sandstone is different from the conventional stress intensity factor approach and a new shear criterion with the consideration of the conjugate shear plane direction is proposed. Base on the mechanical and physical properties parameters from Bohai Bay in China, the stresses around the wells during water injection are calculated to determine the failure mode. And the fracture initiation and propagation pressure are obtained with the model. The results of the study show that the fracture in poorly consolidated sandstone during water injection is dominated by shear failure, and the fracture is perpendicular to the minimum horizontal stress. The fracture initiation pressure is less than that calculated by the traditional approaches and is related to the in-situ stress, rock strength, water temperature, water injection rate and Biot's constant. The fracture propagation pressure is related to the in-situ stress, fracture length, rock strength, water temperature, water injection rate and permeability of the fracture. Through this study, the maximum injection pressure can be determined during water injection in poorly consolidated sandstone. In addition, this study could also have application in other areas, such as wellbore stability, sand production, frac-packing.

## 1. Introduction

There are a large number of poorly consolidated sandstone oil and gas reservoirs in China (Yue et al., 2010). Waterflooding is a very common practice to enhance oil production in this kind of reservoir. However, during the long-term process of water injection, some reasons (such as suspended particles, bacteria, migration of particles etc.) will lead to formation plugging and permeability reduction near the injection wells (Salehi Mojarad and Settari, 2007; Pang et al., 2013; Su, 2009). In order to enhance the water absorption capability of formation, the water injection pressure needs to be increased. However, the injection pressure should be less than the fracturing pressure. Otherwise, it will cause lots of problems, such as casing failure, caprock damage, the nonuniformity of water propulsion, the reactivation of faults (Linji, 2009; Pereira et al., 2014; Zhang et al., 2009). So it's very essential to estimate the reasonable water injection pressure in poorly consolidated sandstone reservoir. Fractures initiation and propagation in brittle competent rocks is studied well in the past few decades (Adachi, 2007; Guo et al., 2014; Hoek et al., 2014). For the brittle competent rocks, the initiation of fractures is controlled by tensile stress and it's generally considered that the fractures will start to form when the tensile stress exceeds the tensile strength. The propagation of fracture is a brittle fracturing process and fracture. And fracture extension model is usually based on stress intensity factor. However, a thorough understanding of the fracture initiation and propagation in poorly consolidated sandstone is still

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not enough. Some studies show that the hydraulic fracture model for brittle competent rock is not applicable to poorly consolidated or unconsolidated sandstone due to the low strength and other mechanical properties (Agarwal and Shamar, 2011; Chin and Montgomery, 2004; Khodaverdian et al., 2000; Redwan and Rammlmair, 2010; Settari et al., 1992). Shear failure, plastic deformation and the coupling effect near the fracture tip play an important role in the fracture initiation and propagation. Khodaverdian, Lullo, Germanovich observed in experiments that the fracture in poorly consolidated sandstone is quite different from that in brittle competent rocks (Germanovich et al., 2012; Khodaverdian et al., 2009; Lullo et al., 2004). It indicates that the fracture tip propagation in poorly consolidated sand is dominated by fluid invasion and shear failure within a process zone ahead of the tip. This is very different from the fracture propagation process in competent rocks. Because the permeability of competent rocks is usually much less than that of poorly consolidated sandstone and it's hard to form the fluid invasion zone ahead of the fracture tip during hydraulic fracturing. Due to the difference of mechanical and physical properties, the fracture development mechanism in poorly consolidated sandstone is different strongly from consolidated sandstone (Abou-Sayed et al., 2005; Desroches et al., 1993). The traditional calculation method could not be applied directly to calculate fracture initiation and propagation pressure in the poorly consolidated sandstone. Therefore, a new coupled model is presented in which the poroelasticity and thermal effect has been taken into consideration to estimate the fracture initiation and propagation pressure in poorly consolidated sandstone.

## 2. Coupled model for poorly consolidated sandstone during waterflooding

In this paper, we present a coupled model for poorly consolidated sandstone during waterflooding to analyze the effective stresses and failure mode around the injection well. The model incorporates thermal effects due to water injection. In this model, the formation is considered as linear elastic medium. So the stress around the wells can be obtained by superimposing the effective stress calculated with the poroelastic model and the stresses induced by thermal effect. The coupled model is able to deal with single phase flow in permeable porous media and calculate the stresses induced by fluid flow and temperature change. Through the model, the fracture initiation and propagation pressure in poorly consolidated sandstone can be calculated.

### 2.1. Poroelastic model

The poroelastic model is used to obtain the effective stresses induced by in-situ stress and fluid flow. It mainly includes six parts: the equilibrium equations, the fluid flow equation, the constitutive equations, geometric equations, the initial conditions and boundary conditions. In the derivations, the basic hypotheses are:

(1) The formation is fully saturated and considered as elastic medium.
(2) The fluid flow around the water injection well is single-phase flow and the fluid flow confirms to Darcy's law.
(3) The rock density, viscosity and density of fluid is uniformly distributed in the formation.
(4) The criterion for tensile failure is maximum tensile-stress criterion and Mohr-Coulomb criterion is applied for shear failure.
(5) The compressibility of water is taken into consideration.

To simply our model and make it more convenient for engineering application, the plasticity of poorly consolidated sandstones is not taken into consideration. Although this will affect the effective stresses around the well, it indicates that the difference of fracture initiation pressure between plastic and plastic models is small according to the calculation results in Section 6.

During the long effect of waterflooding, the water saturation is getting very high and the oil saturation is nearly close to the residual oil saturation near the water injection well. So it's reasonable to assume that the fluid flow around the water injection well is single-phase flow. The fluid flow obeys Darcy's law while Reynolds number is less than 10 according to seepage flow mechanism. And for water injection, the Reynolds number usually meets the condition. In this model, Darcy's law is used to describe fluid flow.

The wellbore is usually under three in-situ stresses, which include the horizontal maximum in-situ stress, the horizontal minimum in-situ stress and the vertical in-situ stress. The stresses in the formation conform to the equilibrium equations, and it is very convenient to calculate them in the cylindrical coordinate system. These equations are shown in equation (1):

$$\begin{cases} \dfrac{\partial\sigma_r}{\partial r}+\dfrac{\partial\sigma_{\theta r}}{r\partial\theta}+\dfrac{\partial\sigma_{zr}}{\partial z}+\dfrac{\sigma_r-\sigma_\theta}{r}=0 \\ \dfrac{\partial\sigma_{\theta r}}{\partial r}+\dfrac{\partial\sigma_\theta}{r\partial\theta}+\dfrac{\partial\sigma_{\theta z}}{\partial z}+\dfrac{2\sigma_{r\theta}}{r}=0 \\ \dfrac{\partial\sigma_{zr}}{\partial r}+\dfrac{\partial\sigma_{z\theta}}{r\partial\theta}+\dfrac{\partial\sigma_z}{\partial z}+\dfrac{\sigma_{zr}}{r}=0 \end{cases} \tag{1}$$

The three dimension Darcy's Law in homogeneous formation is shown in equation (2):

$$\vec{v} = -\frac{k}{\mu}\nabla p \tag{2}$$

The continuity equation of fluid can be shown as,

$$\frac{\partial(\rho\phi)}{\partial t}+\nabla\cdot\left(\rho\vec{v}\right)=0 \tag{3}$$

For the compressible fluid, the relationship between the water density and pore pressure can be written in equation (4):

$$\frac{\partial\rho}{\partial t}=\rho_0\frac{\partial(cp)}{\partial t} \tag{4}$$

From equations (2)–(4), and $\rho$, $\mu$ is assumed to be constant, the fluid flow equation in three dimensions can be expressed in equation (5):

$$\frac{\partial(\phi\mu cp)}{\partial t}=\nabla\cdot(k\nabla p)=\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial p}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial\theta}\left(k\frac{\partial p}{\partial\theta}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial p}{\partial z}\right) \tag{5}$$

The failure is controlled by the effective stresses for the saturated porous media. According to the poroelastic theory, the effective stresses are related to the strains by the generalized form of Hooke's law (compressive stress is positive). For an isotropic material, these relations are,

$$\sigma'_{ij}=-\lambda\varepsilon_v\delta_{ij}-2G\varepsilon_{ij} \tag{6}$$

where $\sigma'_{ij}$ is the effective stress tensor, and the effective stresses are related to the total stresses by the generalized Terzaghi principle as shown in equation (7):

$$\sigma'_{ij}=\sigma_{ij}-\alpha\delta_{ij}p \tag{7}$$

The geometric equations in the cylindrical coordinate system