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A 3D numerical model for studying the effect of interface shear failure on hydraulic fracture height containment

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ABSTRACT

Prediction of hydraulic fracture geometry is a difficult challenge and of great importance in oil engineering. Based on finite element method, a 3D fluid–solid coupling model is established with ABAQUS code for simulating hydraulic fracturing problems. A typical fracturing process of a well in Daqing Oilfield in China is performed with the model. The obtained bottomhole pressure curve almost coincides with the field measured data, and thus the accuracy of the model is verified. The effect of interface shear failure on fracture height containment is studied. The results indicate that when the shear strength of interface is lower than a critical value, obvious slippage between barrier layer and pay layer occurs, the fracture tip becomes blunted, and thus the fracture height is controlled. Our work can provide a new understanding of complex crack propagation in rock and will benefit the design of hydraulic fracture treatment in Oilfield.

1. Introduction

Hydraulic fracturing technology is an essential way of reservoir stimulation (Economides and Nolte, 2000). For vertical fracture, the mechanism of fracture height containment is of critical importance. Investigations on the factors controlling fracture height have been conducted (Smith et al., 2001). Pseudo-3D models are widely used and it is found that the minimum in-situ stress and rock elastic modulus are the most significant factors affecting fracture configuration (Gu and Siebrits 2008). When fracture reaches the interface between barrier layer and pay layer, sliding may occur due to shear failure at the interface. This is another likely mechanism of fracture height containment (Daneshy, 2009). The fracture behavior around a frictional interface was studied and the criterion of fracture re-initiation is dominantly related to the confining stress on the interface (Lam and Cleary, 1984). Assuming the fracture shape is elliptic along the plane normal to the minimum in-situ stress and on the basis of linear fracture mechanics, it is found that hydraulic fracture will penetrate through the interface or extend along formation interface when fracture length is larger than a critical value (Zhao and Chen, 2010). But fully 3D numerical simulation about the effect of interface shear failure on hydraulic fracture height containment is not found in the literatures to our knowledge.

For further study, we use 3D numerical modeling to analyze this topic and quantitative results are derived. A fluid–solid coupling finite element model of hydraulic fracturing is established based on ABAQUS code. The solid deformation of rock material, the seepage flow in porous media, and the fluid flow in the fracture are considered in the model. Damage mechanics is used to predict the fracture initiation and propagation. Our developed user-subroutine is incorporated into ABAQUS for simulating the fracturing fluid viscosity change when the proppant concentration increases. A hydraulic fracturing process of a horizontal well in Daqing Oilfield in China is simulated with the model. The obtained bottomhole pressure curve is consistent with field measured data. The correctness of the model is verified. The effect of shear failure of interface between layers on fracture height containment is studied and analyzed. The results show that if the shear strength of interface is lower than a critical value, the slippage along the interface will occur, leading to the blunted fracture tip. Thus, the fracture height is confined.

2. Mathematical model

2.1. Basic coupled fluid–solid equations

The total stresses of rock satisfy the equilibrium equation expressed in the following form (Malvern, 1969):

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$$\sigma_{ij,j} + f_i = 0 \tag{1}$$

where σ_{ij} is the total stress component, and f_i is the body force component. The comma means differentiation and the repeated index j, means summation according to Einstein's summation convention.

The mass conservation equation of porous fluid is written as (Malvern, 1969)

$$\frac{\partial}{\partial t}(\rho_w \phi) + (\rho_w \phi v_{wi})_{,i} = 0 \tag{2}$$

where ρ_w is the density of porous fluid, ϕ is the porosity and v_{wi} is the seepage flow velocity component.

According to Darcy's law, the velocity of seepage flow is proportional to the gradient of porous pressure in the following form (Marino and Luthin, 1982):

$$v_{wi} = -\frac{1}{\phi g \rho_w} k (p_{w,i} - \rho_w g_i) \tag{3}$$

where k, p_w, and g_i represent the hydraulic conductivity (Neupauer and Dennis, 2010), the porous pressure and the gravity acceleration vector component respectively.

The relationship between solid stress and porous pressure satisfies the effective stress principle (Economides and Nolte, 2000)

$$\bar{\sigma}_{ij} = \sigma_{ij} - p_w \delta_{ij} \tag{4}$$

where $\bar{\sigma}_{ij}$ is the effective stress component, and δ_{ij} is the Kronecker delta.

2.2. Damage model

The cohesive elements based on damage mechanics are used to simulate the fracture behavior. The damage initiation of rock is described by the following quadratic stress criterion (Turon et al., 2006):

$$\left\{\frac{\langle \sigma_n \rangle}{\sigma_n^0}\right\}^2 + \left\{\frac{\sigma_s}{\sigma_s^0}\right\}^2 + \left\{\frac{\sigma_t}{\sigma_t^0}\right\}^2 = 1 \tag{5}$$

where σ_n is the normal stress, σ_s and σ_t are the shear stresses in two shear directions, σ_n^0 is the tensile strength of rock, σ_s^0 and σ_t^0 represent the shear strength of rock in two shear directions. The symbol $< >$ is used to signify that compressive stress state does not cause damage, that is

$$\langle \sigma_n \rangle = \begin{cases} \sigma_n & \sigma_n \ge 0 \\ 0 & \sigma_n < 0 \end{cases} \tag{6}$$

The linear damage evolution law is adopted to simulate the rate at which the material stiffness is degraded after the damage initiation criterion is reached, that is

$$E = (1-D)E_0 \tag{7}$$

where E and E_0 represent the damaged and original elastic modulus of the element respectively. D is the damage factor of the material. It can be expressed as (Zhang et al., 2010a)

$$D = \frac{d_m^f (d_m^{\max} - d_m^0)}{d_m^{\max} (d_m^f - d_m^0)} \tag{8}$$

where d_m^f, $d_m^{\max}$ and d_m^0 refer to the displacement at complete failure, the maximum displacement value during the loading history and the displacement at damage initiation respectively.

Similar to the Darcy's law, the fluid flow velocity in the fracture has a linear relation to the fluid pressure (Hagoort et al., 1980; Dean and Schmidt 2009).

All the equations above are coupled together. Fluid flow may lead to the stress condition of formation change, and deformation of rock may affect the seepage flow in the reservoir and fluid flow in the fracture. The equations for describing the coupled two effects are non-linear. Finite element method (Zienkiewicz and Taylor, 2005) is used to solve the equations. The 8 node hexahedron elements are used, and there are 4 nodal unknowns at each node, i.e. displacements in 3 directions of Cartesian coordinate system and pore pressure. A set of corresponding incremental finite element formulas was derived and solved with the Newton–Raphson iteration method, and more details were described by Zhang et al. (2010b).

3. Numerical verification

A hydraulic fracturing process of a horizontal well in Daqing Oilfield in China is studied with the present model. The simulation domain is constructed with three layers as shown in Fig. 1. The thickness of pay layer is 4.2 m and sandwiched between two barrier layers. The simulation domain is symmetric about the middle plan of the pay layer, and the vertical dimension of the domain (80 m) is much less than the depth of the well (1500 m). As a result, the computational model is only taken the low half of the whole model. The length, width and height of the computational model are 200 m, 20 m and 40 m respectively. The numbers of grids along the three directions are 150, 10 and 30 respectively.

The pump rate of fracturing fluid is 3.5 m^3/min, and all the concerned lithological parameters are provided from Daqing Oilfield. The proppant concentration increases gradually as shown in Table 1. The relation between the viscosity of fracturing fluid and proppant concentration is expressed as (Adachi et al., 2007)

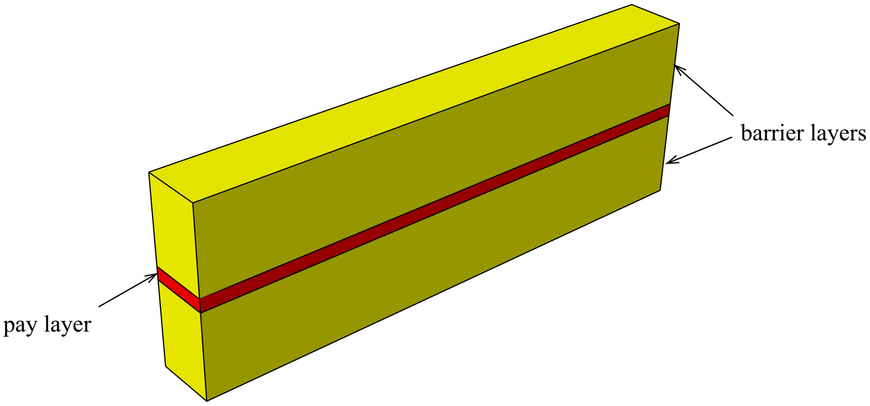

Fig. 1. Sketch of the simulation domain.