The Influence of Biot Coefficient on In-situ Stress Field in the Process of Oil and Gas Production in Low Permeability Oilfield

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Abstract. Biot coefficient is one of the important parameters that describe the elastic deformability of pores in rocks. Numerical simulation is applied in this paper to study the effect of Biot coefficient on the in-situ stress field disturbance in the process of oil and gas production in low permeability oilfield. And study results reveal the effect of variations of Biot coefficient on the in-situ stress field disturbance in the process of oil and gas production in low permeability oilfield: the value of principal stress decreases with the increase of Biot coefficient; and the deflection angle of principal stress before and after production shows linear increase with the increase of Biot coefficient.

Keywords: Biot coefficient; In-situ stresses; Numerical simulation; Low permeability; Block 5 of Bonan Oilfield.

1. Introduction
As one of the important parameters that describe the elastic deformability of pores in rocks, Biot coefficient refers to the porous elastic coefficient of porous medium of rocks and reflects the contributions of pore spaces to the overall deformation of rocks (Kilmentos et al., 1995; Hongkui Ge et al., 2001; Shengjie Li, 2005; Zhonggao Ma, 2008). Presently, studies on Biot coefficient of rocks are rare and mainly focus on the effects of variations of confining pressure and pore pressure on Biot coefficient, ignoring the effects of different lithologies and permeability, etc. (Yuanfang Cheng et al., 2015; Zhiqing Zhang et al., 2016; Jingshou Liu et al., 2018). Especially, there are no systematical research results on effect of variations of Biot coefficient on the in-situ stress field. Numerical simulation is applied in this paper to study the effect of Biot coefficient on the in-situ stress field disturbance in the process of oil and gas production in low permeability oilfield. And study results reveal the effect of variations of Biot coefficient on the in-situ stress field disturbance in the process of oil and gas production in low permeability oilfield and expand research ideas and methods to understand variations of the in-situ stress field correctly in the process of oil and gas production.

2. Biot Coefficient
Biot coefficient refers to the porous elastic coefficient of porous media (rocks) and is the key
parameter for hydraulic fracturing design, sanding prediction, optimized design of well trajectory, and analysis and calculation of wellbore stability (Baoping Zhang, 1996; Zhongping Li et al., 2012; Yuanfang Cheng et al., 2015). Yingfa Lu et al., (2005) proved characteristics of anisotropic damage for Biot coefficient based on tests of triaxial water injection and drainage. The value of Biot coefficient of reservoir is determined by its internal structure (porosity, rock composition, fluid medium, pore structure and grain characteristics, etc.). Micro cracks mainly distribute in low permeability rocks with throats in curved or flaky shapes, therefore cracks are easy to close when pressured, the response sensitivity of Biot coefficient of low permeability rock to effective stress is much higher than that to high-middle permeability rock and the Biot coefficient of low permeability rock decreases rapidly with the increase of effective stress (Fangyuan Cheng et al., 2015). According to the compositional structures, rocks can be divided into granular rock (sandstone, mudstone) and chemically cemented crystalline rock (limestone). As for granular rock and crystalline rock, the mechanisms of deformation when pressured are of great difference. Slippage (dislocation) and deformation of grains and compressional deformation of pores will happen in granular rock when pressured; only compressional deformation of pores (no slippage or dislocation of grains) will happen in crystalline rock, and if the crystalline rock is cemented tightly, no deformation of pores will exist. Therefore, the Biot coefficient is 0 for tightly cemented crystalline rock and is 1 for granular rock if the state of floating rock is achieved (Zhongping Li et al., 2012).

3. Mathematical Model of Stress Field Simulation

Interaction of fluid and stress field exists in the process of oil and gas production for low permeability oilfield (Jie Tian et al., 2005, Wu Chen et al., 2013, Jianwei Feng et al., 2019). Therefore, mathematical model of stress field simulation includes equations describing reservoir fluid flow, rock stress and definite conditions.

3.1. Non-stable Equation of Fluid Flow in Reservoir

Fluid flow in reservoir follows Darcy’s Law, which is described in the following equation:

\[ \nabla \cdot \left[ \frac{k \rho}{\mu} (\nabla P_f - \rho g \nabla D) \right] + \rho q = \rho (\theta + \phi \beta) \frac{\partial P_f}{\partial t} \tag{1} \]

where \( k \) is rock permeability, \( \rho \) is fluid density, \( \mu \) is fluid viscosity, \( P_f \) is pore pressure, \( g \) is acceleration of gravity, \( D \) is depth calculated from a certain datum plane (downwards is positive), \( \theta \) is the rock matrix compression coefficient, \( \phi \) is rock porosity, \( \beta \) is fluid compression coefficient, \( q \) is a source term in unit volume of reservoir, \( t \) is time.

3.2. Stress Equilibrium Equation

In three dimensions, stresses at any point in the fluid-containing reservoir must satisfy the following equation:

\[ \sigma_{ij,j} + (aP_f \delta_{ij})_j + f_i = 0 \tag{2} \]

where \( \sigma_{ij} \) is effective stress tensor, \( a \) is Biot coefficient, \( P_f \) is pore pressure, \( \delta_{ij} \) is Kronecker function, \( f_i \) is external load.

The Equation (1) and (2)and definite conditions constitute the mathematical model of stress field simulation in porous medium.

4. Numerical Modeling Process

4.1. The Geological Model

The target layer of this study is the third segment of the Shahejie Formation (Member SIII) in the Block 5 of the Bonan Oilfield. Member SIII is poor in permeability with an average thickness of
10m and a burial depth of 3100m. The lithology assemblage consists of fine sandstone and siltstone. The average air permeability is $8 \times 10^{-3}$ $\mu$m$^2$ and the average porosity is 15.6%. The dimensions of geological models are 1200m×1200m×10m.

4.2. Model Parameters and Boundary and Initial Conditions

The parameters in the model are listed in Table 1. The parameters are chosen based on testing results and the existing data of study area. The existing study results are calculated to determine Biot coefficient. The range of Biot coefficient is 0.5~0.8 through calculation with 0.7 corresponding to porosity of 15.6% (Shouwei Zhang, 2011; Shouwei Zhang et al., 2010).

| Variables | Value       | Description                      |
|-----------|-------------|----------------------------------|
| $k$       | $7.5 \times 10^{-15}$ m$^2$ | Rock permeability                |
| $\phi$    | 15.6%       | Rock porosity                    |
| $\rho$    | 1000 kg/m$^3$ | Fluid density                    |
| $\mu$     | 1.00 mPa·s  | Dynamic viscosity                |
| $g$       | 9.81 m/s$^2$ | Acceleration of gravity          |
| $\theta$  | $1.50 \times 10^{-5}$ MPa$^{-1}$ | Rock matrix compression coefficient |
| $\beta$   | $4.50 \times 10^{-5}$ MPa$^{-1}$ | Fluid compression coefficient    |

Boundary confinement of the model: as for the stress field, normal direction confinement is adopted in left and right boundaries. The upper boundary is not confined; while the lower boundary (3100 m) is fully confined in all directions. As for the fluid field, the upper and lower boundaries are all impermeable boundaries. The left and the right boundaries are the given flow boundaries. The original condition of model can be calculated according to the actual measurement of pore pressure and stress data of monitoring wells.

4.3. Simulation Process

FLAC(2D) software is applied in numerical simulation. Single well production mode is applied in this simulation and stress field is in stable tensional state. Biot coefficient changes in the range of 0.5~0.8 (0.5, 0.6, 0.7, 0.8) in the simulation to study the variation characteristics of the in-situ stress caused by variations of Biot coefficient in the process of oil and gas production in low permeability oilfield.

5. Analyses of Simulation Results

5.1. Biot Coefficient’s Effect on the Magnitude of Principal Stress

Simulation results demonstrate that stress field varies obviously near production well under the condition of stable single well production and tensional stress. The maximum principal stress ($\sigma_H$) (absolute value) increases symmetrically from the production well to surroundings with the fastest increase in the direction of X axis (Fig. 1). And $\sigma_H$ (absolute value) decreases with the increase of Biot coefficient (Fig.1). The amplitude difference between the absolute value of the $\sigma_H$ and the initial stress increases in the horizontal direction of model with the Biot coefficient increasing from 0.5 to 0.8. Specifically, when Biot coefficient is 0.5, the amplitude difference is about 1.4MPa; when Biot coefficient is 0.8, the amplitude difference is about 3MPa. Statistics demonstrate a fast decrease of $\sigma_H$ near the production wellhead. With the increase of the distance from the wellhead, the absolute value of $\sigma_H$ first increases rapidly, then slowly (Fig.2). Simulation results also show a similar variation characteristics of that the minimum principal stress ($\sigma_h$) with the maximum principal stress($\sigma_H$).
5.2. Biot Coefficient’s Effect on the Direction of Principal Stress

The directional deflection of $\sigma_H$ increases obviously with the increase of Biot coefficient (0.5~0.8) in the process of oil and gas production in low permeability oilfield; and directional deflection of $\sigma_H$ before and after production shows linear increase with the increase of Biot coefficient (Fig. 3). When Biot coefficient is 0.5, the maximum directional deflection of $\sigma_H$ is 0.8°; when Biot coefficient is 0.8, the maximum directional deflection of $\sigma_H$ increases to 1.5°, which is about twice the original value. Statistics demonstrate that the directional deflection of $\sigma_H$ increases rapidly near the production wellhead. With the increase of the distance from the wellhead, the directional deflection of $\sigma_H$ increases rapidly in the opposite direction, and then increases slowly and tends to be stable (Fig. 4).
Figure 4. Direction variations of principal stress (\(\sigma_H\)) with Biot coefficient

Variations of Biot coefficient have great effect on directional deflection of \(\sigma_h\). Similar to the directional deflection of \(\sigma_H\), with the increase of Biot coefficient, the directional deflection of \(\sigma_h\) increases obviously.

6. Conclusions

Biot coefficient has great influence on the disturbance of in-situ stress field in the process of oil and gas exploitation in low permeability area. The effect of Biot coefficient on the variations of the principal stress amplitude and directional deflection in horizontal direction is greater than other physical properties of rocks.

In the process of oil and gas production in low permeability oilfield, the value of principal stress decreases with the increase of Biot coefficient, and the direction deflection of principal stress before and after production shows linear increase with the increase of Biot coefficient.

As a major production enhancement measure in the development of low permeability oil fields, fracturing design based on the stress field distribution characteristics. Therefore, it is important to study the influence of Biot coefficient on the stress field for the efficient development of low permeability oil fields.

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