Numerical Simulation of Temporal and Spatial Evolution of Stress Field in Unconsolidated Sandstone Oil Reservoir

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Abstract. Casing damage in the process of oilfield development is a serious problem, which is affected by geological structure, production technology and many other factors. To prevent casing damage, it is necessary to master the space-time evolution law of reservoir in-situ stress field, to provide support for casing damage prevention. Based on the perseeage-stress coupling theory, taking the actual reservoir block as the research object, the change law of the in-situ stress field in unconsolidated sandstone reservoir is obtained through the fluid-solid coupling numerical simulation of the reservoir, and the internal correlation between the stress field and casing damage is analysed. The research results provide theoretical guidance for the formulation of casing damage prevention measures in the research block.

Keywords: Fluid-solid coupling; Numerical simulation; Geostress; Casing damage.

1. Introduction

The regional structure of Qudi Oilfield is located on the nose-like structure of Qudi on the southern slope of Huimin Sag, Jiyang Depression. The actual oil-bearing area is 21.8 square kilometres, and the petroleum geological reserve is 30.12 million tons. Qudi Oilfield was put into development in 1995 and is loose. Sandstone complex fault block reservoirs, the main oil-bearing intervals are the Guantao Formation, the second member, the third member and the fourth member of Shahejie Formation.

Casing damage is a technical problem affecting the development of Qudi Oilfield. Sets of variable wells are mainly concentrated in Q9G3 (2) and Q104 blocks. Among them, there are 44 casing-damaged wells in block Qu9, accounting for 50.5% of the casing-damaged wells, accounting for 36.7% of the number of wells in this block (120), and block Qu104 has 23 casing-damaged wells, accounting for 26.4% of the casing-damaged wells. The other 20, accounting for 23.1%. According to statistics of 87 casing damage wells: 50 casing damage occurred in the production well section, mainly concentrated in Qu104 block and Qu 9 block, accounting for 57.5%; 28 casing damage occurred above the production well section, accounting for 32.2%; 9 cases occurred below the production well section, accounting for 10.3%. The research on casing damage prediction and prevention and control involves multiple disciplines such as structural geology, geodynamics, rock mechanics, petroleum geology, material mechanics, elastoplastic mechanics, etc., as well as modern numerical methods, materials and geometric nonlinear theories, Finite element method and computer science, etc., and this research has penetrated mechanics, mathematics and physics and other mathematical science theories. It is a comprehensive, wide-span interdisciplinary research on marginal subjects.
Since it is difficult to simulate the stress and deformation process of casing in complex formations with physical model experiments, to reveal the mechanism of casing damage in loose sandstone reservoirs, this paper uses computer numerical simulation technology as the main method and modern in-situ stress field research to predict and prevent the occurrence of damage to the formation casing [1-4].

2. Mathematical Model of Stress Evolution of Oil Reservoir

2.1. Mathematical Model of Seepage Field

The basic differential equation of the simplified oil-water two-phase black oil model considering the deformation of the medium [5]:

Oil composition equation:

\[ \nabla \cdot \left[ \frac{K_{ro}}{\mu_o} (\bar{p} - \rho_o g \bar{D}) \right] + \frac{\phi}{\rho_o} \frac{\partial \rho_o}{\partial t} + \frac{\phi}{\rho_o} \frac{\partial S_o}{\partial t} + \frac{S_o(1-S_o)}{1+\epsilon_v} \frac{\partial \epsilon_v}{\partial t} + \frac{q_o}{\rho_o} = 0 \]  

Water composition equation:

\[ \nabla \cdot \left[ \frac{K_{rw}}{\mu_w} (\bar{p} - \rho_w g \bar{D}) \right] + \frac{\phi}{\rho_w} \frac{\partial \rho_w}{\partial t} + \frac{\phi}{\rho_w} \frac{\partial S_w}{\partial t} + \frac{S_w(1-S_w)}{1+\epsilon_v} \frac{\partial \epsilon_v}{\partial t} + \frac{q_w}{\rho_w} = 0 \]

Where, \( K \) is absolute permeability, \( K_{ro} \) is relative permeability, \( \mu \) is viscosity, \( p \) is fluid pressure, \( \rho \) is density under standard conditions, \( S \) is saturation of oil and water respectively, \( D \) is elevation, \( \epsilon \) is volume strain, \( \phi_0 \) is initial porosity, \( q \) is production of oil and water under standard conditions and \( C_a \) is the mass quality of oil and water phase respectively, \( a \) is phase state.

2.2. Mathematical Model of Stress Field

The basic equations of the stress field of porous media include: equilibrium differential equations, geometric equations, and physical equations.

The balance equation is:

\[ \frac{\partial \sigma_{ij}}{\partial x_i} - f_{x_i} = 0 \quad i, j = 1, 2, 3 \]  

Where, \( \sigma \) is the effective stress tensor, \( x \) is the three coordinate directions of \( x, y, z \), and \( f_{x_i} \) is the volume force in the \( x \)-direction.

Considering the geometric conditions of deformation, when the elastic body is deformed, by analyzing the relationship between the deformation component and the displacement component of the micro-element body, the geometric equation is established as:

\[ \epsilon_{ij} = \frac{1}{2} \left( \nabla u_{i,j} + u_{j,i} \right) \]  

Reservoir rock and soil often exhibit nonlinear elastic and elastoplastic mechanical behavior. According to plastic mechanics, the relationship between stress increment and strain increment in a plastic state is:

\[ \{d\sigma\} = [\sigma] \{d\epsilon\} = [\sigma]_{ep} \{d\epsilon\} \]  

\[ [D_p] = \frac{[\sigma] \left( \frac{\partial \sigma}{\partial \epsilon} \right)^T [\sigma]}{A + \frac{\partial \sigma}{\partial \epsilon} \left( \frac{\partial \sigma}{\partial \epsilon} \right)^T [\sigma]} \]

Where, \( \epsilon \) is strain component, \( u \) is displacement component and \( [D]_{ep} \) is elastic-plastic matrix.

For the ideal elastoplastic model, \( A=0 \) in the above formula; under the condition that the Drucker postulate is established, the plastic potential energy function \( Q=F \), at this time \( [D]_{ep} \) is a symmetric matrix.

2.3. The Relationship between Media Permeability and Pore Pressure and Effective Stress

Studies have shown that the empirical formula between the permeability coefficient tensor and the pore deformation in the fluid-solid coupling problem of the reservoir is:

\[ K_{ij} (\Delta \phi) = K_{ij}^0 \exp \left[ -\alpha \Delta \phi \right] \]  

(7)
Where, $K$ is the permeability coefficient tensor, $\alpha$ is the coupling coefficient and $\Delta \phi$ is the increase in porosity of the medium.

3. Simulation of Temporal and Spatial Evolution of In-situ Stress Field

3.1. Establishment of Geological Model

The research object is Qu104-X3 block of Qudi Oilfield. Qu104-X3 block oil reservoir average buried depth: 1791.2-2395.5 m, average formation temperature: 88 °C, average porosity: 18%, average permeability: $1.53.6 \times 10^{-3} \mu m^2$, crude oil viscosity: 13.8MPa·s, crude oil density: 0.8627g /cm$^3$, stratum salinity: 46781mg/l. According to the reservoir sensitivity evaluation report of Well Qu 104-708, there are moderately strong acid, weak water and weak alkali sensitivity on Sha 3 and Sha 4, and the critical salinity of non-velocity sensitivity and salt sensitivity is 20,000 mg/L. The physical and mechanical parameters of rocks in this study are shown in Table 1 below.

Table 1. Log Interpretation of Reservoir Physical Parameters in Block Qu104-X3.

| Ng4$^2$ | Porosity% | Density of Crude oil (g/cm$^3$) | Viscosity (MPa·s) |
|---------|------------|---------------------------------|------------------|
| 35.4    | 3045       | 0.96                            | 1900             |
| Ng5$^2$ | Porosity% | Density of Crude oil (g/cm$^3$) | Viscosity (MPa·s) |
| 33.3    | 2897       | 0.976                           | 3000             |
| Ng6$^1$ | Porosity% | Density of Crude oil (g/cm$^3$) | Viscosity (MPa·s) |
| 32.7    | 2365       | 0.972                           | 5000             |

Figure 1 shows the simulation area and well location map, and Figure 2 shows the geological model of the simulation area.

![Figure 1](image-url)

Figure 1. The range of simulation area and well location distribution map.

There are 9 layers in the Qu104-X3 block (small layers combined), which are divided into S3-1, S3-2, S3-3, S4S-2, S4S-3, S4S-4, S4Z-1, S4Z-2, S4Z-3, the corresponding numerical simulation layers are as follows: the first layer to ninth layer. The physical and mechanical parameters of casing, cement ring, and formation are shown in Table 2.

Table 2. Casing-cement ring-formation physical and mechanical parameters.

|          | E (MPa) | $\mu$ (MPa) | $\psi$ (°) | Compressive strength (MPa) |
|----------|---------|-------------|------------|---------------------------|
| Casing   | $2.0 \times 10^{11}$ | 0.33        |            | 700                       |
| Cement ring | $3 \times 10^{10}$ | 0.26        | 26.3       | 12.8                      |
| Sand rock | $2.1 \times 10^{10}$ | 0.23        | 22.7       | 18.6                      |
| Mud rock | $9.1 \times 10^{9}$ | 0.34        | 18.9       | 22.2                      |


3.2. Numerical Model
The number of grids in the x-direction of the model is 125, and the number of grids in the y-direction is 63. The model is divided into 9 simulation layers in the longitudinal direction. The total number of grids is 70875. The thickness of the oil layer is different and the plane difference is large.

The stress calculation adopts the following stress boundary and displacement boundary:
- Displacement boundary: the bottom surface of the model is constrained, the surrounding horizontal displacement is constrained, and the top surface is a free surface.
- Stress boundary: vertical in-situ stress is applied according to the self-weight stress of the overlying strata; horizontal in-situ stress is based on the statistical data of the in-situ stress measurement survey of Shengli Oilfield (the relationship between the horizontal maximum compressive stress and the depth \( h \) is \( 2.5+0.0236h \text{MPa} \); the horizontal minimum compressive stress and the depth Relationship \( 1.5+0.045h \text{MPa} \)).

Initial and boundary conditions of seepage field:
The initial oil saturation is 0.65, the mass flow around the top and bottom layers is 0, the water injection well is the flow boundary, the production well is the constant bottom pressure boundary.

4. Fluid-solid Coupling Simulation Results

4.1. History Fitting of Qu104-X3 Block Production
The selected simulation block has a total of 26 production wells. The production started on February 1, 1996 and ended on March 31, 2011. The result is as follows.
From the above simulation results, the error of each index fitting result of the entire block is within 5%, which satisfies the calculation requirements of reservoir engineering, indicating that the established model and parameters are correct, and can be used as a later mechanism analysis research model.

4.2. Simulation Results of Stress Field
The calculation results of the x-stress field in different periods obtained by the numerical simulation are shown in Figure 4 below.

![Stress in X direction.](image)

It can be seen from the above figure that as the development progresses, the horizontal X-direction stress of the oil layer is increasing, and the stress in each area is mainly affected by the flow field of the well. There are different degrees of stress concentration near each production well, which will as a result, these wells are subjected to uneven concentrated loads.

Similar to the X-direction stress change law, as the development progresses, the horizontal Y-direction stress of the oil layer is increasing, and the stress in each area is mainly affected by the flow field of the well. There are different degrees of stress concentration near each production well. This will cause these wells to bear unevenly concentrated loads.

Similar to the horizontal stress change trend, as the development progresses, the Z-direction stress of the oil layer is increasing, and the stress in each area is mainly affected by the flow field of the well. There are different degrees of stress concentration near each production well. These wells will be subjected to uneven concentrated loads. Because the three directions of ground stress are concentrated near the production wells, and according to the logging data of this block, there are many mudstone intervals in this block, and these mudstones are under development. If it absorbs water, it will expand and the strength will drop sharply. Under the same ground stress, it will enter the plastic failure stage first and transfer the load to the casing [6,7]. Therefore, this kind of mudstone section is relatively developed in the reservoir. The load generated by the stress will eventually act on the casing. When the casing is under concentrated load, when the strength of this concentrated load exceeds the squeezing strength of the casing, the casing will be squeezed, that is, squeeze occurs.

5. Conclusions
Based on the geology and well data of the well group in Qujiuguan 3 and Qu104-X3 blocks in Qudi Oilfield, a geological model of the well group was established, and the evolution of the in-situ stress field during the injection-production process was carried out. Numerical simulations were made. The main conclusions are as follows:

(1) As the development progresses, the horizontal x-direction displacement of the oil layer gradually increases, and the overall horizontal displacement is increasing, especially in the near-wellbore zone, where the oil layer displacement changes most obviously;

(2) This difference in interlayer displacement is likely to induce layer-to-layer sliding of some layers and shear on the casing, thereby inducing another casing failure mode: shear casing damage;
As the development progresses, the horizontal x-direction stress of the reservoir is increasing, and the stress in each area is mainly affected by the flow field of the well. There are different degrees of stress concentration near the production wells, which will cause these wells to withstand failures.

During the development process, the three-directional in-situ stress of the oil layer was concentrated near the production well. The three-directional stress concentration in Well Qu104-X316 was the most obvious, but in fact, the well has undergone casing deformation in 2008.

According to the change law of fluid-solid coupling in injection-production process, the main measures to prevent casing damage in the research block are as follows:

1. Control the bottom hole pressure of the production well, reduce the production pressure difference, at the beginning of the development, take high production Wells flow pressure, when the reservoir pressure is generally lower further reduce the bottom hole flow pressure, which can avoid the large range of in-situ stress change and make the casing under extrusion pressure;

2. Control the production-injection ratio or production well daily fluid volume can avoid the high extrusion pressure on casing due to the rapid decline of formation pore pressure caused by the excessive production-injection ratio.

3. Use high-strength casing or pre-stressed casing in the production section of the oil layer to reduce the possibility of casing damage.

4. In the process of development, selecting reasonable combination of layers can avoid the stretching or shear casing damage caused by interzone water absorption and production-injection.

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