Introduction

Reservoir geomechanics is a bridge between geological knowledge and engineering technology in the integration of geology and engineering (Hu, 2005; Yang et al., 2019). In-situ stress is the most important part in geomechanics research, especially the present-day in-situ stress analysis. Understanding the present-day in-situ stress field is the key in deeply buried tight reservoirs, and its role runs through the whole process of exploration and development.

The KS gas field is located in the Kelasu structural belt (KSB) of the northern Tarim Basin, which is a typical deeply buried area of abundant natural gas resources. However, the KS gas field is located in a complex geological environment with extremely strong compression deformation, large numbers of faults and fractures. Within this area, the layers are deeply buried, dip angles are high, the conglomerate and gypsum salt strata are thick, the porosity and permeability are low, and the temperature, pore pressure and stress concentration are high (Yang et al., 2018; Tian, 2019). Therefore, it is necessary to carry out systematic in-situ stress study in the KS gas field for better understanding the reservoir condition.

A set of in-situ stress evaluation method for complex structural area is formed through one-dimensional geomechanical modeling (1DGM) and three-dimensional in-situ stress field simulation (3DIFS). Firstly, the heterogeneous 1DGM of the entire wellbore is carried out based on the logging calculation and hydraulic fracturing data. The geomechanical properties of the whole well are defined in this method, and then the 3D finite element method is used for in-situ stress field study. Finally, constructive suggestion on well trajectory optimization is provided based on the analysis of present-day in-situ stress field. The KS10 gas reservoir is taken as an example in this study, which is one of an important development blocks in the Tarim Oilfield (Figure 1).

Methods

⚫ 1D heterogeneous mechanical modeling

In this study, the logging calculation and hydraulic fracturing data are used to get the stress state within a single well. According to the practical experience of Tarim Oilfield, the combined spring model is greatly suitable for the Kuqa foreland thrust belt with strong compressions. The calculation model of combined spring is as follows (Li and Zhang, 1997):

$$
\begin{align*}
S_h &= \frac{\mu}{1-\mu} \left( S_v - \alpha P_p \right) + \frac{\mu E_s}{1-\mu^2} + \frac{\mu E_{sh}}{1-\mu^2} + \alpha P_p \\
S_h &= \frac{\mu}{1-\mu} \left( S_v - \alpha P_p \right) + \frac{E_s}{1-\mu^2} + \frac{E_{sh}}{1-\mu^2} + \alpha P_p
\end{align*}
$$

(1)

Figure 1 (A) A sketch of Kelasu structural belt (KSB), KSB can be divided into the AWT section, BZ section, DB section, and KS section from west to east. (B) Seismic section through KS10 structure. It shows a typical thrust imbricated structure, and there is a set of gypsum salt strata with great changes of thickness distribution. (C) Contour map of KS10 gas reservoir.
where, $S_h$ is the maximum horizontal principal stress, MPa; $S_v$ is the minimum horizontal principal stress, MPa; $S_z$ is the vertical principal stress, MPa; $P_r$ is the pore pressure, MPa; $\mu$ is Poisson's ratio, dimensionless; $E$ is the modulus of elasticity, GPa; $\alpha$ is the Biot coefficient, dimensionless; $\zeta_h$ and $\zeta_h$ are the maximum and minimum principal stress, respectively, dimensionless.

Generally, the $\zeta_h$ and $\zeta_h$ are difficult to be directly determined. The value of $S_h$ at specific locations are determined by hydraulic fracturing data, which is used as the basis of constraint and scale to indirectly determine the value. Generally, in the process of hydraulic fracturing, the shut-off pressure is the value of fracture closure pressure, which is equal to the $S_h$, and the calculation method of the $S_h$ is as follow (Zoback, 2007):

$$
\begin{align*}
S_h &= P_c \\
S_h &= 3S_h - P_r - P_f
\end{align*}
$$

(2)

where $P_c$ is the shut-down pressure, MPa; $P_r$ is the fracture reopening pressure, MPa.

- Simulation of 3D heterogeneous stress field

The workflow for finite element numerical simulation method is as follow: Firstly, the geological body is discretized into finite elements. The elements are connected by nodes, and the corresponding rock mechanical parameters are given to these elements. The basic variables of the field function in the study area include displacement, stress and strain. According to the boundary stress conditions and node balance conditions, the solution of the equation group with node displacement as the unknown quantity and total stiffness matrix as the coefficient is obtained, and the displacement on each node is calculated, and then the stress and strain values in each element can be calculated. The simulation of 3D heterogeneous stress field mainly includes the following five steps (Ju et al., 2019):

1. Establishing geological model based on the logging data, seismic data and regional geological data.
2. Constructing the 3D heterogeneous rock mechanics field.
3. Establishing 3D heterogeneous mechanical model by put the mechanical parameters into the finite elements.
4. Imposing constraints and loads, and debugging reasonable boundary conditions.
5. Checking the reliability of simulation results.

Example

The KS10 gas reservoir is taken as an example in this study, the main reservoir is Bashijiqike formation of Cretaceous ($K_1bs$). The direction of the $S_H$ can control the extension of natural fractures, including its direction and length, the $S_h$ affects the opening status of the fractures, and the horizontal difference stress is the key controlling factor for volume fracturing (Zhang et al., 2016).

Simulation results of present-day in-situ stress of KS10 gas reservoir can be seen in Figure 2, the lateral distribution characteristics of the $S_H$, $S_h$ and the horizontal stress difference of is similar to each other and the stress distribution is discrete. The stress value is lower in the high part of the anticline, and gradually increases in the wings. The $S_h$ within top surface of $K_1bs$ in the KS10 gas reservoir is about 110~160MPa, and the horizontal stress difference is about 35~50MPa.

The three principal stresses obviously change with depth. The principals, $S_h$, $S_h$ and $S_v$ gradients are 2.2MPa/100m, 2.6~2.7MPa/100m, and 2.5MPa/100m, respectively. The $S_v$, $S_h$ and $S_v$ values are about 138MPa, 165MPa and 152MPa respectively, showing a dominant $S_h > S_v > S_h$, which is a strike-slip faulting stress regime (Type III).

The direction of the $S_H$ in the KS10 gas reservoir significantly changes, and the regularity of the change is obvious. The direction of the $S_H$ is NW-SE-trending in the western section, the high part of the middle anticline is nearly N-S-trending, and gradually changes to NE-SW-trending in the eastern section. From northern area to southern area, the stress direction also changed, basically from nearly N-S-trending to NE-SW-trending.
Figure 2 Simulation results of present-day in-situ stress. (A) Maximum horizontal principal stress. (B) Minimum horizontal principal stress. (C) Difference of horizontal stress. (D) Direction of maximum horizontal principal stress. Dotted lines are the projection lines of faults.

It is necessary to consider the present-day in-situ stress state in the well trajectory design and correctly evaluate the wellbore stability so as to design a reasonable mud density and ensure safe, fast and accurate drilling. The KS10 structure is one of thrust structures in the KS area of Kelasu structural belt. The KL8 and KL1 structures are superposed on the KS10 structure (Figure 1). Low stress area of KS10 gas reservoir lies to the north of the projection line of KL1 and KL8 faults, i.e., in the superimposed area of hanging wall. Considering geological factors and reservoir geomechanics, the low stress area is the sweet spot for well location deployment. If the way of vertical well is adopted, faults such as the KL1 and KL8 and the thicker salt layer will be drilled, which may bring a series of complex engineering problems and safety risks to the drilling.

Figure 3 (A) Simulation analysis of wellbore stability of vertical well, there is only a very narrow safe mud window (no more than 0.3) in salt layer. (B) Simulation analysis of wellbore stability of highly deviated well, the mud window of the salt layer is wide and the borehole is stable.

Through the simulation of the wall stability of vertical wells and highly deviated wells (Figure 3), there is only a very narrow safe mud window in kumglimu group (salt layer), if the well is designed as a highly deviated well with the wellhead to the south and inclining to the north, shallow faults can be avoided, and the thickness of the salt layer to be drilled is relatively thinner. Moreover, the mud window of the salt layer is wide and the borehole wall is stable, which has a positive effect on safe, stable and rapid drilling. Therefore, the plan of using highly deviated well in Well K1002 is better than that of vertical well. The practice shows that Well K1002 has high oil and gas production, which
proves that the trajectory optimization of highly deviated wells considering the present-day in-situ stress state is reasonable and effective.

Conclusions

The tight sandstone reservoir in the Kelasu structural belt is deeply buried with high stress concentration. The mechanism of in-situ stress generally belongs to strike slip type (Type III) in KS gas field. The present-day in-situ stress value is high and the distribution is discrete. The minimum horizontal principal stress is generally above 110MPa, and the horizontal stress difference is greater than 35MPa. The maximum horizontal principal stress direction is generally nearly NE-direction, and the local direction is NW or NE direction. The low stress area is the sweet spot for well location deployment. Therefore, the well trajectory optimization considering the current in-situ stress state is helpful to reduce the complex accidents, avoid the potential engineering risks, quickly drill into the target formation.

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References


