Study on in-situ stress distribution in complex shale reservoirs

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Abstract. The shale reservoir in boxing depression has developed faults and fissures, and the distribution of in-situ stress is complex. Therefore, in this paper, studies on in-situ stress distribution of the shale reservoir in boxing depression based on the actual logging data, and maps the changes of in-situ stress and lateral pressure coefficient with the depth. The results show that the maximum horizontal principal stress in the study area is about 58~67MPa. The minimum horizontal principal stress is about 55~63MPa. The in-situ stress in the study area has a linear relationship with depth as a whole. The stress state accords with the relationship that the vertical principal stress is greater than the maximum horizontal principal stress is greater than the minimum horizontal principal stress. The coefficient of lateral pressure has a hyperbolic relation with depth. The research results can provide scientific basis for well pattern layout of oil and gas exploration and development in shale reservoir and reservoir reconstruction plan design.

1. Introduction

All manuscripts must be in English, also the table and figure texts, otherwise we cannot publish your paper. Please keep a second copy of your manuscript in your office. When receiving the paper, we assume that the corresponding authors grant us the copyright to use the paper for the book or journal in question. Should authors use tables or figures from other Publications, they must ask the corresponding publishers to grant them the right to publish this material in their paper. In-situ stress refers to the stress state and distribution of rock mass in natural state, which is a necessary condition for oil well exploration, development and evaluation. Research on the distribution rule of in-situ stress has become one of the urgent problems to be solved in deep-well oil and gas exploitation [1]. Therefore, many scholars have carried out relevant researches. Chen et al. [2] obtained the in-situ stress model of coal seam in the northern margin of Qinshui basin through comprehensive inversion, and realized the calculation of in-situ stress under the condition of silent wave time difference. Wang et al. [3] modified the in-situ stress of the target reservoir to make the optimized model more accurately reflect the distribution characteristics of in-situ stress in the reservoir. Wang et al. [4] conducted linear regression analysis on the relationship between multiple stress parameters and depth, and obtained that the relationship between shallow lateral pressure coefficient and depth was in line with hyperbola., Wei et al. [5] systematically analyzed the horizontal maximum, minimum and vertical...
stress of coal seam in Yuwang district based on measurement data and geomechanical model. However, most of the current studies are focused on shallow strata, and do not consider the impact of reservoir heterogeneity on in-situ stress. Therefore, in this paper, carried out numerical calculation of rock mechanics parameters and three-way stress, etc. for the shale reservoir in boxing depression, and conducted numerical simulation study of in-situ stress in the research area with ANSYS software.

2. Study on in-situ stress in study area

2.1. Overview of the research area
Boxing depression is located at the southwest end of Dongying sag, which belongs to the second-order negative structural unit and settlement center in Dongying sag, and is the main body of boxing area. Under the control of Gaoqing and Pingnan faults, an asymmetric graben with graben overlap in the southeast of the fault depression in the west of boxing depression and steep southeast of the west of boxing depression is formed.

2.2. Acquisition of Rock Mechanics Parameters
Before solving rock mechanics parameters, shear wave time difference is first obtained, which is usually obtained through the transformation of longitudinal wave time difference. The transformation formula is shown in equation (1).

\[
\Delta t_s = \frac{\Delta t_p}{[1 - 1.15 \frac{1}{\rho} + \frac{1}{\rho^3}]^{15}}
\]  

In the formula, \(\Delta t_s\) and \(\Delta t_p\) is the time difference of shear and longitudinal waves, \(\mu/s/ft\); \(\rho\) is the density of formation rock, \(g/cm^3\):

The calculation of main rock mechanics parameters is shown in the formulas (2) and (3).

\[
E_d = \frac{\rho(3\Delta t_s^2 - 4\Delta t_p^2)}{\Delta t_s^2(\Delta t_s^2 - \Delta t_p^2)} \times 9.299 \times 10^7
\]  

\[
\mu_d = \frac{0.5\Delta t_s^2 - \Delta t_p^2}{\Delta t_s^2 - \Delta t_p^2}
\]

Dynamic and static elastic modulus and poisson's ratio transformation of shale reservoir rocks are shown in equations (4) and (5).

\[
E_s = 0.37E_d + 6580
\]

\[
\mu_s = -1.4129\mu_d + 0.6617
\]

2.3. Calculation of in-situ stress in study area
Huang Rongzun's in-situ stress calculation model is adopted. The in-situ stress calculation is shown in the formulas (6) and (7).

\[
\sigma_h = \frac{\mu_s}{1 - \mu_s}(P_0 - \alpha P_p) + \beta_1(P_0 - \alpha P_p) + \alpha P_p
\]

\[
\sigma_h = \frac{\mu_s}{1 - \mu_s}(P_0 - \alpha P_p) + \beta_1(P_0 - \alpha P_p) + \alpha P_p
\]

Fanye 1 well in the study area calculation results are shown in table 1.
Table 1 rock mechanical parameters and stress calculation results

| Num | Top depth /m | Bottom depth /m | Interpretation | E/MPa | μ | ρ/(g/ cm³) | Max/MPa | Min/MPa |
|-----|--------------|-----------------|----------------|-------|---|------------|---------|---------|
| 1   | 3249.4       | 3261.5          | Dry layer      | 15792.3 | 0.21355 | 2.51770 | 58.82708 | 55.45236 |
| 2   | 3261.5       | 3270.5          | Oil layer      | 17304.2 | 0.21612 | 2.52927 | 58.25351 | 54.68658 |
| 3   | 3270.5       | 3348            | Dry layer      | 17351.4 | 0.21756 | 2.53754 | 59.46214 | 55.89122 |
| 4   | 3348         | 3349            | Oil layer      | 17359.2 | 0.21708 | 2.53510 | 59.69951 | 56.02663 |
| 5   | 3349         | 3434.6          | Dry layer      | 18469.9 | 0.22402 | 2.56921 | 60.94332 | 57.13141 |
| 6   | 3434.6       | 3450.4          | Oil layer      | 21033.4 | 0.22572 | 2.57779 | 60.21100 | 56.04111 |
| 7   | 3450.4       | 3490.2          | Dry layer      | 18603.3 | 0.22651 | 2.58154 | 62.62404 | 58.71353 |
| 8   | 3490.2       | 3494            | Oil layer      | 19019.1 | 0.22441 | 2.57121 | 62.26863 | 58.26131 |
| 9   | 3494         | 3542.7          | Dry layer      | 19009.2 | 0.23053 | 2.60132 | 63.88661 | 59.89101 |
| 10  | 3542.7       | 3547.5          | Oil-bearing aquifer | 20834.9 | 0.22868 | 2.59220 | 62.74466 | 58.48409 |
| 11  | 3547.5       | 3558            | Dry layer      | 19212.9 | 0.23736 | 2.63487 | 65.64448 | 61.62951 |
| 12  | 3558         | 3560.8          | Oil layer      | 17677.7 | 0.22256 | 2.56210 | 64.16744 | 60.25769 |
| 13  | 3560.8       | 3622            | Dry layer      | 18227.4 | 0.23796 | 2.63781 | 67.14175 | 63.21341 |

2.4. Numerical simulation of in-situ stress

Well Fanye 1 in Boxing Depression is selected as the research object, and the strata in the study area are divided into 13 layers according to the rock mechanics parameters, as shown in Fig.1. For convenience of study, simplify the model: assume that the strata in the study area are ideal strata; do not consider creep effect when calculating in-situ stress; use prism as loading model, and R = 50m cylinder as single well calculation model.

![Fig 1. Stratigraphic division model](image)

The maximum and minimum horizontal principal stress nephograms in the study area are shown in Figs. 2 and 3.

![Fig. 2 Maximum horizontal principal stress nephogram of Well Fanye 1](image)
According to figures 2 and 3, the maximum horizontal stress in the study area is 58.53~67.10MPa, and the minimum horizontal stress is 55.07~62.92MPa. Stress increases with depth.

The maximum horizontal stress calculated by huang’s model is between 54.57 and 71.28MPa, and the minimum horizontal stress is between 50.75 and 67.15MPa. The horizontal stress error between calculated value and simulated value is within 10%, which indicates that the research results are reliable.

3. Study on the Distribution Rule of in-situ Stress

3.1 Variation of in-situ stress with depth

The measured data show that the vertical stress is basically equal to the weight of overlying strata. It can be seen that the vertical stress increases with the depth.

Fig.4 scatter diagram of partial horizontal stress and depth and its fitting curve

Linear fitting of partial calculated stress and depth was carried out, and its scatter diagram and fitting curve were shown in fig.4. The general fitting equation is shown in equations (8) and (9).

\[
\sigma_H = 0.0247H - 22.574 \quad (R^2 = 0.7262)
\]

\[
\sigma_h = 0.0231H - 21.095 \quad (R^2 = 0.6401)
\]

The regression coefficients of the equations are all greater than or equal to 0.8, indicating that there is a good linear relationship between the maximum and minimum horizontal principal stress and depth, that is, it increases linearly with the increase of depth.

3.2 Variation of Side Pressure Coefficient with Depth

The lateral pressure coefficient K refers to the ratio of horizontal stress to vertical stress. The maximum, minimum and average lateral pressure coefficients are expressed by \( K_H \), \( K_h \), \( K_a \). The expression of the average lateral pressure coefficient is shown in equation (10):

\[
K_a = \frac{\sigma_H + \sigma_h}{2\sigma_v}
\]

Assuming the ratio of horizontal stress to vertical stress in the study area

\[
K_a = \frac{\sigma_H}{\sigma_v} + b
\]
Let \( H = \frac{1}{X} \), then there is

\[
K_a = aX + b \tag{12}
\]

Linear regression analysis of the data in the study area showed that \( a = 115.15, B = 0.6911 \).

Namely \( K_a = \frac{115.15}{H} + 0.6911 \) \( \tag{13} \)

Similarly, the inner and outer lines of the lateral pressure coefficient can be obtained, as shown in Fig. 5. For ease of comparison, the dotted line part of the figure gives the curve of the ratio of the average horizontal principal stress to the vertical stress varying with the depth in all regions of the Hock-Brown world.

![Fig. 5 Side pressure coefficient versus depth curve](image)

From Fig. 5, it can be seen that the curve of lateral pressure coefficient varying with depth in the study area basically coincides with the Hooker-Brown curve; in the study area, three main stresses are observed at the state of \( \sigma_V > \sigma_H > \sigma_H \).

4. Conclusion

(1) The maximum horizontal principal stress in the study area is about 58~67MPa. The minimum horizontal principal stress is about 55~63MPa, and the total in-situ stress increases with the increase of depth, in which the vertical stress is linear with the depth. Although the maximum and minimum horizontal stress increase linearly with the increase of depth as a whole, however, due to tectonic action, there will be a small range of fluctuations.

(2) The variation of the ratio of horizontal stress to vertical stress in the study area with depth is basically consistent with the Hooker-Brown curve, that is, the shallow lateral pressure coefficient has a large dispersion and fluctuation range, while the deeper the lateral pressure coefficient continues to decrease, the fluctuation range also decreases, showing a trend of transition to hydrostatic pressure state. The average lateral pressure coefficient of the study area is finally stable at about 0.8, which indicates that there is a certain tectonic effect in the interval.

(3) Despite the influence of lithology and tectonic movement, the stress state in the study area still conforms to \( \sigma_V > \sigma_H > \sigma_H \). Where the horizontal stress difference is large, most of them are zones where cracks and faults breed and develop. Therefore, in the process of deployment of oil and gas development network in this area, the heterogeneity of in-situ stress distribution should be fully considered, and the fracture pressure and the orientation of faults and fractures should be reasonably predicted.

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