Study on in-situ stress of heterogeneous shale reservoir

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Abstract. In-situ stress is the important basis for reservoir evaluation. Most of the in-situ stress solutions are based on well logging data and rock mechanics experiments. In fact, according to the actual geological condition, heterogeneity is an important factor affecting shale reservoir recovery. However, the effect of rock heterogeneity on stress is less considered. In this paper, taking well FY1 in block FY1 of Dongying depression as an example, the method of overall mechanical model analysis is used to analyze the in-situ stress of the study area, and the influence of rock heterogeneity on in-situ stress is studied, which reflects the true distribution of in-situ stress in shale reservoir. The research results show that, the minimum horizontal principal stress and the maximum horizontal principal stress increased slightly with the increase of depth, and the vertical stress increases gradually with depth, which is in direct proportion.

1. Introduction
Shale reservoirs have the characteristics of low porosity, ultra-low permeability, and natural fracture development [1]. Therefore, shale reservoirs are usually exploited by hydraulic fracturing [2]. According to the current status of shale oil exploration in North America, the research of shale oil production mainly focused on the effectiveness of fracturing methods [3], which deriving many fracturing stimulation theories. With the progress of fracturing technology, the commercial development of shale oil in North America has made a great breakthrough. In view of this, fracturing is especially important to the exploration of shale gas wells, and the degree of fracture development directly affects the development efficiency of shale reservoirs. It is worth noting that the in-situ stress is the basis for studying fracture propagation law and designing fracturing perforating scheme.

The genesis of in-situ stress is complex, and the distribution is very irregular. At present, the main research method is based on the logging data, using the method of mathematical statistics to analyse the distribution law of in-situ stress field. The distribution of in-situ stress is affected by many factors, including depth, geological structure, mechanical properties of rock and so on. Among which the depth and mechanical properties of rock are the main factors. E.T.Brown [4] summarized measurement results of in-situ stress in different areas, put forward the change rule of vertical stress with depth, and drew the curve of the ratio of horizontal and vertical in-situ stress with depth. Sheorey [5] put forward the calculation model of in-situ stress and pointed out that the horizontal stress was closely related to the
Elastic modulus. The larger the elastic modulus was, the higher the horizontal stress was. Wang Chenghu [6] modified and optimized the parameters based on the theoretical model of Sheorey. Zhu Huanchun [7] studied the stress distribution formula under the action of elastic modulus and depth based on the measured in-situ stress data. Analysing the previous works, important improvements have been achieved on the in-situ stress. However, few researchers investigated the in-situ stress in heterogeneity shale reservoir. Therefore, in this paper, the rock mechanics parameters of heterogeneity shale reservoir were obtained based on logging data. Furthermore, the in-situ stress was simulated, and the simulation results were analysed.

2. Survey of the research area
Dongying depression is located in the southeast of Jiyang depression, with qingtuozi uplift in the East, Luxi uplift and Guangrao uplift in the south, Qingcheng uplift in the west, Chenjiazhuang uplift and Binxian uplift in the north, 90km in length from east to west, 65km in width from south to north, and 5850km² in area. The 3249-3604m interval of well FY1 in block FY1 is the study object in this paper. This interval is located on the fourth sand section. The lithology is mainly shale with a small amount of sandstone. With the increase of depth, the rock mechanics parameters such as Poisson's ratio and Yang's modulus change. Therefore, the shale reservoir is heterogeneous, which has a corresponding effect on the in-situ stress.

3. Study on in-situ stress in study area

3.1. Rock mechanics parameters
The reservoir rock mechanical parameters mainly include dynamic Poisson's ratio, dynamic elastic modulus, static Poisson's ratio, and static elastic modulus.

3.1.1. Acquisition of shear wave time difference. The shear wave time difference is obtained according to conventional logging data, and its formula is as follows:

\[
\Delta t_s = \frac{\Delta t_p}{1 - 1.15 \left( \frac{1}{\rho} + 1 \right) \left( \frac{\rho}{\rho_s} \right)^{1.5}}
\]  

(1)

Where, \( \Delta t_s \) is the time difference of formation shear wave, \( \mu s/ft \); \( \Delta t_p \) is the time difference of formation compressional wave, \( \mu s/ft \); \( \rho \) is the density of formation rock, \( g/cm^3 \).

3.1.2. Calculation of rock elastic parameters. According to the acoustic time difference and rock elastic mechanical parameters, the rock elastic parameters can be calculated as follows:

Dynamic Poisson's ratio:

\[
\mu_d = \frac{1}{2} \left( \frac{\Delta t_s^2 - 2\Delta t_p^2}{\Delta t_s^2 - \Delta t_p^2} \right)
\]  

(2)

Dynamic elastic modulus:

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

(3)

Shear modulus:

\[
G = \frac{\rho}{\Delta t_s^2} \times 9.299 \times 10^7
\]  

(4)

Static petrophysical parameters should be used in the analysis of the whole mechanical model of the research reservoir and in the actual engineering. The static rock mechanical parameters are obtained
from the transformation of dynamic mechanical parameters. The transformation formulas of dynamic and static mechanical parameters are as follows:

\[
\mu_s = 0.4929 \mu_d + 0.064 \\
E_s = 0.2403E_d + 11118
\]

(5)  (6)

Where, \(E_s\), \(E_d\) are static and dynamic elastic modulus of rock; \(\mu_s\), \(\mu_d\) are static and dynamic Poisson's ratio of rock.

According to the conventional logging data, the time difference of formation shear wave varies with the depth. The reservoir rock mechanical parameters are causally related to the time difference of formation shear wave. Therefore, the reservoir rock mechanical parameters change with the increase of depth, and the reservoir shows heterogeneous.

3.1.3. Basic parameters of formation rock. According to the calculation of logging data, the basic rock parameters, and in-situ stress of well FY1 are shown in table1.

| Layer number | Top depth /m | Bottom depth /m | Static Poisson's ratio | Static modulus /MPa | vertical stress /MPa | Maximum horizontal principal stress /MPa | Minimum horizontal principal stress /MPa |
|--------------|--------------|-----------------|-----------------------|----------------------|----------------------|-----------------------------------------|-----------------------------------------|
| 1            | 3249.430     | 3261.420        | 0.220                 | 17114.359            | 79.440               | 64.938                                  | 60.032                                  |
| 2            | 3261.420     | 3290.740        | 0.219                 | 17784.838            | 79.944               | 64.914                                  | 59.867                                  |
| 3            | 3290.740     | 3320.380        | 0.218                 | 18354.108            | 80.663               | 65.135                                  | 59.952                                  |
| 4            | 3320.380     | 3340.000        | 0.220                 | 17602.571            | 81.264               | 66.111                                  | 61.013                                  |
| 5            | 3340.000     | 3360.840        | 0.218                 | 18622.358            | 81.748               | 65.819                                  | 60.528                                  |
| 6            | 3360.840     | 3370.540        | 0.218                 | 18643.585            | 82.121               | 66.117                                  | 60.796                                  |
| 7            | 3370.540     | 3390.720        | 0.217                 | 18442.304            | 82.495               | 66.464                                  | 61.167                                  |
| 8            | 3390.720     | 3450.400        | 0.216                 | 19347.319            | 83.465               | 66.692                                  | 61.177                                  |
| 9            | 3450.400     | 3501.600        | 0.216                 | 18897.480            | 84.811               | 68.002                                  | 62.484                                  |
| 10           | 3501.600     | 3559.000        | 0.214                 | 19373.797            | 86.141               | 68.661                                  | 62.999                                  |
| 11           | 3559.000     | 3590.700        | 0.213                 | 17976.673            | 87.227               | 70.250                                  | 64.800                                  |
| 12           | 3590.700     | 3604.000        | 0.208                 | 19651.562            | 87.776               | 69.427                                  | 63.689                                  |

It can be seen from table 1 that the in-situ stress is different at different depths. In detail, the horizontal maximum principal stress, and the horizontal minimum principal stress increase slightly. On the other hand, the vertical stress increases significantly with depth. As a result, the reservoir shows heterogeneity in the in-situ stress.

3.2. Reservoir model of the study area

According to the formation lithology of well FY1 and the formation rock mechanics parameters, the 3249 -3604 m depth is divided into 12 layers, and the three-dimensional model is built with the size of 60m × 60m around the well pad.

Due to the complexity of the sedimentary process of the formation, the following assumptions should be taken as the premise to simplify the model:

1. Geological factors such as folds and bulges are ignored in a small horizontal plane, the reservoir dip angle is assumed to be 0°.
2. In a small horizontal plane, it is assumed that the horizontal direction of the formation rock is the same.
3. The creep property of rock is not considered in the calculation of in-situ stress.
3.2.1. Determination of model stress boundary conditions. In the actual geological environment, the horizontal in-situ stress increases with depth, but the heterogeneity and discontinuity of vertical distribution of formation rock lead to the uneven distribution of in-situ stress. The horizontal in-situ stress increases along vertical distribution, but it will fluctuate in a small range due to the change of rock mechanical parameters. In order to accurately reflect the stress boundary conditions, the following methods were used to determine the boundary conditions for the model.

3.2.2. Finite element simulation. The stress distribution of the well and the surrounding area was clearly obtained by simulation. The cloud chart of stress distribution around the target layer is shown in Figure 2-3.

As seen from Figure 2-3, the maximum horizontal principal stress of target layer is 73-77MPa, and the minimum horizontal principal stress is 68-71MPa. The simulation of in-situ stress accurately restores
the three-dimensional ground stress distribution in this area, which makes up for the lack of formation
ground stress data in the process of conventional logging, and provides an effective ground stress basis
for the unconventional oil and gas reservoir reconstruction.

3.3. Analysis of calculation results
After the calculation, the data of the maximum and minimum horizontal principal stress at the center of
3249 -3604 m in well FY1 is extracted along the depth direction, and the curve of the stress with depth
is obtained as shown in Figure 4.

![Figure 4. Stress curve of central axis of well FY1.](image)

As seen from Figure 4, the horizontal maximum principal stress increases slightly with the increase
of depth, due to the change of rock mechanical parameters. Therefore, stress value can be approximated
as constant. Meanwhile, the variation law of horizontal minimum principal stress is similar. However,
the vertical stress increases with formation depth, which is approximately proportional.

4. Conclusion
(1) According to the conventional logging, the dynamic rock mechanics parameters were calculated,
and the static rock mechanics parameters were calculated by the transformation formulas.
(2) The stress distribution of the well and the surrounding area was simulated based on the calculated
rock mechanics parameters. The result shown that the maximum horizontal principal stress of target
layer is 73-77MPa, and the minimum horizontal principal stress is 68-71MPa. The simulation results
provide an effective ground stress basis for the unconventional oil and gas reservoir reconstruction.
(3) The horizontal maximum principal stress and the horizontal minimum principal stress in the study
area increase slightly with the increase of depth, but the increase range is small. However, the vertical
stress increases with the increase of the depth of the formation, which is approximately proportional.

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