Experimental analysis and logging evaluation of in-situ stress of mud shale reservoir-- Taking the deep shale gas reservoir of Longmaxi Formation in western Chongqing as an example

Haiyan Mao1,2, Tongtong Luo3, Fuqiang Lai1,2,*, Guotong Zhang1,2, Lulu Zhong1,2

1 National and Local Joint Engineering Research Center of Shale Gas Exploration and Development, Chongqing Institute of Geology and Mineral Resources, Chongqing, 401120, China
2 Key Laboratory of Complex Oil and Gas Field Exploration and Development, Chongqing University of Science and Technology, Chongqing 401331, China
3 CNPC Chuanqing Geological Exploration and Development Research Institute, Chengdu, 61000, China

*Corresponding author Email: laifq1982@163.com

Abstract. The complex structural conditions of marine shale in Western Chongqing area lead to the problems of insufficient understanding of pore structure, unclear direction of in-situ stress and poor fracturing effect, which lead to the difficulty of shale gas development. Based on the experimental study and logging data, the calculation model of in-situ stress is established. Finally, the influencing factors of in-situ stress are analyzed. The results show that the distribution of three-direction stress in the target interval is \( \sigma_H > \sigma_v > \sigma_h \), and the experimental and logging results are consistent. As a whole, the in-situ stress tends to decrease with the increase of depth, with little fluctuation and good continuity. The fragility characteristics of the reservoir are relatively good, and it is easier to form various cracks that are widely developed.

1. Introduction

Shale reservoirs are low-porosity, low-permeability rocks that require large-scale fracturing to achieve commercial capacity. The in-situ stress is a key factor in the fracturing transformation. In the process of reservoir reconstruction, the state of formation in-situ stress field and the mechanical properties of rocks determine the direction, shape and orientation of fracture extension, and which affect the stimulation effect of fracturing. The study of in-situ stress distribution in oil and gas reservoirs has become an important subject in the process of exploration and development. In recent years, many scholars in China have begun to pay attention to the study of in-situ stress, and have made great progress. At present, the methods of conducting geostress research mainly include logging interpretation method, core experiment method, hydraulic fracturing method, numerical simulation method, etc. The experimental method is the most direct means of determining in-suit stress. However, the test is expensive, and the number of measurements is very limited due to geological conditions, core data, etc., and continuous geostress profiles cannot be obtained. Logging data has the advantages of continuous depth, rich information and low cost. Therefore, it is often combined with logging data to study the in-suit stress of
2. Research on rock mechanics parameters

2.1. Experimental acquisition of static rock mechanics parameters

The rock mechanics characteristics of shale are the key factors affecting the overall exploitation of shale gas. Shale gas reservoirs must pass large-scale volumetric fracturing to form complex seam networks in the formation to achieve the purpose of benefit development. In order to obtain more accurate rock mechanics data, this study completed 6 sets of uniaxial rock mechanics experiments. When doing uniaxial rock mechanics experiments, the samples of each group were selected, which were vertically coring, and processed into a diameter of about 2.54 cm and a length of about 5.00 cm. The experimental results are shown in Table 1. The uniaxial Young's modulus of the core is mainly distributed in \(2.727 \times 10^4\) MPa to \(3.674 \times 10^4\) MPa, with an average of \(3.1645 \times 10^4\) MPa, and the Poisson's ratio is mainly distributed in 0.188 to 0.302, with an average of 0.243.

| Sample number | Density g/cm | Young's modulus \(\times 10^4\) MPa | Poisson's ratio |
|---------------|--------------|-------------------------------------|----------------|
| YX-2017-92-02 | 2.655        | 2.812                               | 0.188          |
| YX-2017-105-02| 2.653        | 2.727                               | 0.205          |
| YX-2017-112-06| 2.621        | 3.537                               | 0.250          |
| YX-2017-114-01| 2.566        | 3.674                               | 0.215          |
| YX-2017-135-02| 2.592        | 3.298                               | 0.302          |
| YX-2017-135-04| 2.592        | 2.939                               | 0.295          |

Triaxial stress experiments can obtain rock mechanics parameters under realistic formation stress conditions (Compressive strength, modulus of elasticity and Poisson's ratio), which can be used to calculate the "brittleness index" of shale, or to use the stress-strain curve to judge the denaturing characteristics of the core[1]. Six rock samples were selected for triaxial compressive strength experiments. The test results are shown in Table 2. It can be seen from the table that the Young's modulus is distributed in \(2.821 \sim 3.691 \times 10^4\) MPa, with an average of \(3.199 \times 10^4\) MPa, and the Poisson's ratio is distributed in 0.192 ~ 0.262, with an average of 0.216. Overall, it shows higher Young's modulus and lower Poisson's ratio, which preliminarily indicates that Longmaxi-Wufeng shale in Dazu area has better brittle characteristics.

| Sample number | Density g/cm | Confining pressure MPa | Compressive strength MPa | Young's modulus \(\times 10^4\) MPa | Poisson's ratio |
|---------------|--------------|------------------------|--------------------------|-------------------------------------|----------------|
| YX-2017-92-01 | 2.655        | 79.1                   | 376.09                   | 2.821                               | 0.230          |
| YX-2017-105-01| 2.653        | 79.2                   | 328.95                   | 3.226                               | 0.262          |
| YX-2017-121-01| 2.645        | 79.4                   | 376.09                   | 3.232                               | 0.192          |
| YX-2017-121-02| 2.645        | 79.4                   | 360.59                   | 3.076                               | 0.205          |
| YX-2017-135-01| 2.592        | 79.4                   | 332.20                   | 3.691                               | 0.195          |
| YX-2017-135-03| 2.592        | 79.4                   | 327.62                   | 3.148                               | 0.214          |

2.2. Dynamic rock mechanics parameter calculation

Although the rock mechanics parameters obtained through laboratory research have high precision, the resources consumed are large, and the obtained parameters are discontinuous. It is easier to obtain the
parameters by using logging data, and the formation information is continuous. And because the underground rock is under triaxial stress, the rock properties are closer to the static test conditions of the rock, so the experimental test results are also essential[2]. Therefore, in the engineering, the dynamic method must be combined with the dynamic method to make up for the shortcomings of the static mechanical parameters measured by the static method [3].

Rock strength mechanical parameters mainly include Young's modulus, Poisson's ratio, shear modulus, bulk modulus, volumetric compressibility of formation and skeleton, etc. We can calculate these rock elastic parameters according to the wave theory, the longitudinal and transverse wave time difference measured by DSI of dipole shear wave imaging logging and the volume density obtained by density logging [4].

\[
G = 9.29 \times 10^4 \cdot \frac{\rho_b}{\Delta t_s^2} \quad (1)
\]

\[
K = G \cdot \frac{3\Delta t_s^2 - 4\Delta t_p^2}{3\Delta t_p^2} \quad (2)
\]

\[
E_d = G \cdot \frac{3\Delta t_s^2 - 4\Delta t_p^2}{\Delta t_s^2 - \Delta t_p^2} \quad (3)
\]

\[
\mu_d = \frac{0.5\Delta t_s^2 - \Delta t_p^2}{\Delta t_s^2 - \Delta t_p^2} \quad (4)
\]

In the formula: \(G\) is the dynamic shear modulus, GPa; \(K\) is the dynamic bulk modulus, GPa; \(E_d\) is the dynamic Young's modulus, GPa; \(\mu_d\) is a dynamic Poisson's ratio, dimensionless; \(\rho_b\) is the density of the formation rock, g/cm\(^3\); \(\Delta t_s\) is the shear wave time difference, \(\mu s/m\); \(\Delta t_p\) is the longitudinal wave time difference, \(\mu s/m\).

2.3. Dynamic and static rock mechanics parameter conversion

In this paper, the static values obtained by experimental tests and the dynamic data calculated by well logging data are used for regression analysis. Establish a conversion formula for dynamic static Poisson's ratio and Young's modulus parameters. In this study, the data points are small, and the parameters obtained by the indoor triaxial core experiment are not good when the Poisson's ratio dynamic and static parameter conversion is performed. Therefore, we use the uniaxial test results of the core to study the dynamic and static parameters of Poisson's ratio. After removing some data with large error, the dynamic and static parameter conversion analysis and modeling are obtained. The linear relationship is shown in Figure 1.

![Figure 1. Dynamic and static parameter conversion diagram](image-url)
It can be seen from the figure that there is a good correlation between the dynamic Young’s modulus and the static Young’s modulus. There is a good negative correlation between the static Poisson’s ratio and the dynamic Poisson’s ratio, and the correlation coefficient reaches 0.8614. The conversion relationship is as follows:

\[
E_s = 0.8658E_d - 6.4356 \\
\mu_s = -1.4028\mu_d + 0.6686
\]

In the formula: \(E_s\) is the static modulus of elasticity, GPa; \(E_d\) is the dynamic elastic modulus, GPa. \(\mu_s\) is the static Poisson’s ratio, \(\mu_d\) is the dynamic Poisson’s ratio.

Through the dynamic and static transformation of the elastic parameters and strength parameters of rock mechanics, a series of logging conditions that are closer to the actual situation of underground rock and meet the needs of actual engineering are obtained. Continuous logging of single well interpretation profiles can be established by using logging data and dynamic and static transformation relationships combined with software. It has great practicability in practical applications, and it is more convenient to obtain data and more continuous in change [5]. From Figure 2, it can be seen that Longmaxi Formation Long1 and Wufeng Formation reservoirs have good brittleness.

![Figure 2. Rock mechanics parameter logging interpretation profile](image)

### 3. Calculation of in-situ stress of reservoir

In this study, the core data of the zu202 well was selected for the in-situ stress experiment. By testing the P-wave anisotropy of the full-diameter core level, it is determined that the maximum velocity of the wave velocity is the h-direction and the minimum wave velocity is the H-direction. The rock samples were drilled laterally in the H and h directions, respectively. The maximum and minimum stress values were obtained by using the Kaiser principle. From the experimental results, the three-direction principal stress distribution of 1 small layer and Wufeng Formation is: \(\sigma_H > \sigma_v > \sigma_h\) (Table 3).

| Layered  | Homing depth(Core-0.5m) | Numbering | Three-way principal stress/MPa |
|---------|-------------------------|-----------|-------------------------------|
| Long1   | 3889.58~3889.82         | YX-2017-112 | 106.51 87.17 99.20           |
| Wufeng Formation | 3893.41~3893.61       | YX-2017-134 | 107.37 87.56 99.20           |
The calculation of in-situ stress is usually based on theoretical model. Vertical stress is the stress field caused by the geocenter, which is also called gravity stress field or compressive stress of overlying rock.

\[
\sigma_v = g \int_{h_0}^{H} \rho(h) dh
\]  

(5)

In the formula, \( \sigma_v \) is the vertical ground stress, \( g \) is the gravity acceleration, \( H \) is the formation depth, m; \( h_0 \) is the starting depth of the target layer, m; \( \rho(h) \) is the density of the formation rock at the buried depth \( h \), g/cm³.

The Longmaxi Formation-Wufeng Formation in the Dazu Block of the Western Chongqing is in the normal compaction stage. Therefore, the horizontal in-suit stress is calculated using the Huang's empirical model:

\[
\sigma_H = \mu \left( \sigma_v - \alpha P_p \right) + \beta_1 \left( \sigma_v - \alpha P_p \right) + \alpha P_p
\]

(6)

\[
\sigma_h = \mu \left( \sigma_v + \alpha P_p \right) + \beta_2 \left( \sigma_v + \alpha P_p \right) + \alpha P_p
\]

(7)

In the formula, \( \sigma_H, \sigma_h \) is the horizontal maximum and minimum principal stress, MPa; \( \mu \) is Poisson's ratio, no dimension; \( \alpha \) is the Biot coefficient, dimensionless; \( P_p \) is pore pressure, MPa; \( \beta_1, \beta_2 \) is the tectonic stress coefficient, dimensionless, and it can be inducted by the measured stress value to obtain \( \beta_1=0.75, \beta_2=0.62 \).

The formation pore pressure refers to the pressure of the fluid in the pore fluid of the formation. This paper uses the following empirical formula to calculate formation pore pressure:

\[
P_p = 9.80655 \times 10^{-3} \times 1.437 \times DEP
\]

(8)

In the formula, \( P_p \) is the formation pore pressure, MPa; \( DEP \) is the sampling point depth value, m.

By introducing the overburden strata pressure, Poisson's ratio, effective stress coefficient, formation pressure and tectonic stress coefficient of Well Zu202 into Huang's model, a continuous in-situ stress profile can be obtained (Figure 3). The in-situ stress statistics are shown in Table 4.

| Well name     | Layered | \( \sigma_H \)/MPa | \( \sigma_h \)/MPa | \( \sigma_v \)/MPa |
|---------------|---------|--------------------|--------------------|-------------------|
| Well Zu202    | Long-1\(^1\) | 104.01~107.60      | 91.29~94.83        | 100.55~100.72     |
| Wufeng Formation |        | 97.84~107.53      | 85.16~93.78        | 90.64~100.98      |
Figure 3. Ground force calculation result map

It can be clearly seen from the figure that the three-direction stress distribution of the Long-111-wufeng formation is $\sigma_H > \sigma_v > \sigma_h$. Consistent with the experimental test results. As a whole, the in-suit stress tends to decrease with increasing depth, but the variation is not large, indicating that the stress has good continuity. When $\sigma_H$ is the maximum principal stress, the diagenesis is relatively enhanced, and it is easier to form various cracks that are widely developed [6].

4. Conclusion

(1) In this paper, the mechanical parameters obtained by rock mechanics experiments show that the overall display shows higher Young's modulus and lower Poisson's ratio characteristics. The analysis shows that the reservoir shale in the study area has good brittle characteristics and is easy to form a complex seam by volumetric fracturing.

(2) Through analysis, it is considered that the depth of burial of the formation and the mechanical parameters of the rock have an influence on the ground stress. The in-suit stress decreases with the increase of depth. The in-suit stress calculated by using rock mechanics parameters is consistent with the experimental test results. The magnitude of the in-suit stress of Long-111-wufeng formation is $\sigma_H > \sigma_v > \sigma_h$.

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