Computer modeling of gas shale reservoirs basing on dynamic mechanical characteristics - A Case Study of Well No. 202 in Weiyuan Area of Sichuan Basin

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Abstract. Global shale oil and gas resources are very rich, are becoming an important supplement to conventional oil and gas. However, due to strong plasticity, strong reservoir stress sensitivity and poor stability, easy burst collapse, rupture, card Drilling or well leakage and other phenomena, restricting the development of shale oil and gas resources. In order to improve the safety and efficiency of the shale formation drilling project, This paper uses the rock physics, logging, geology and other disciplines as the theoretical guidance, using the dynamic model to build the method, and the No. 202 well logging data and related research results as an example, the prediction, verification and evaluation of rock mechanics parameters, in-situ stress, wellbore stability and compressibility of the shale formation were carried out respectively. The results show that the rock mechanics model provides the key information for the construction of hydraulic fracturing engineering. There are significant wall collapse phenomena in the well sections of the Well No. 202, and there are significant differences in the maximum and minimum horizontal principal stresses at specific parts. The results of this study are of great significance to the follow-up of shale reservoirs and the design of late fracturing.

1. Introduction
Shale gas has gradually become a new global focus for oil and gas exploration and development due to its advantages of wide distribution, abundant resources and so on [1]. Shale gas reservoir usually has features such as low porosity, low permeability and low brittleness of rocks, etc., so that it is necessary to use the process technologies such as horizontal wells and multi-stage fracturing to improve the reservoir in shale gas exploration and development work [2]. Mud shale reservoir has strong stress sensitivity, poor stability, and is easy to occur sudden collapse, rupture, drill pipe sticking or lost circulation, which seriously restrict the exploitation process of shale oil and gas resources. It can predict the borehole wall stability and compressibility of the shale reservoir by establishing a model with the stress parameters of gas shale, and then we carry out mechanical dynamic analysis and compressibility analysis of the rocks with gas shale, in order to obtain the reliable physical parameters...
of the rocks, improve the safety and efficiency of drilling engineering in the mud shale formation, and promote the formation of fast drilling and borehole.

Currently, the researches on modeling analysis of rock physical parameters of shale reservoir are mainly based on the rock physical parameter analysis method proposed by Rickman [3] et al., which takes the Barnett shale gas reservoir as an example. However, because the Barnett shale mode ratio in North America is not suitable for all shale reservoirs, its application results are different from the measured data, and the practical effect is not good. In recent years, many scholars have made further studies on the mechanical properties of rocks, but the research on the dynamic and static analysis of rock physical parameters is insufficient [4]. The dynamic vertical and horizontal rock physical parameters (Young's modulus, Poisson's ratio, etc.) can reflect the possibility of borehole deformation or fracture under dynamic load, so as to realize accurate analysis on ground stress.

Therefore, based on the conventional logging method and the relationship between logging data and rock mechanical properties, this paper calculates the rock mechanical parameters such as elastic modulus, shear modulus, volume modulus and Poisson's ratio, and further evaluates the formation pressure, ground stress and borehole stability. Then, through the calculation and debugging on the actual data, and the research results at home and abroad, the logging interpretation and analysis of the formation pressure features are carried out, the applicability and reliability of the logging interpretation model of ground stress are compared, and a set of ground stress interpretation methods and processes which are suitable for the shale formation in the study area are verified and proposed.

The study of rock mechanical properties is of great importance to the engineering design in oil and gas drilling, especially it has important reference value and guiding significance for the stability analysis of borehole wall in the drilling process, the hydraulic fracturing and other aspects. For a long time, many scholars have conducted researches in this area, and have produced great results.

2. Study Area

Weiyuan anticline is located in the middle of Sichuan Basin in China, with a large uplift which influences a lot. Its landform coincides with the geological structure which both are controlled by regional geological conditions (figure 1). The main part of the Weiyuan anticline consists of low and towering mountains with deep valley and steep slope, where generally develop karst and valley. The terrain of the whole region is high in northwest and low in southeast. It inclines from northwest to southeast where can be seen two large landform areas of hills and low mountains.

Figure 1. Calculated results of elastic parameters

The study refers to the logging data collected from No. 202 well, which is an appraisal well specially for shale gas in Weiyuan structure. It locates in Xinchang town, Weiyuan county, and on the south wing of the top of Mid-Ordovician. The exposed layer on the surface is the Zhenzhuchong
section of the Ziliujing Formation. This well is to evaluate the shale distribution and gas content of Silurian Longmaxi Formation in the southeastern Weiyuan anticline. The comprehensive logging data have proved that the spatial distribution of high-quality shale is at the bottom of Silurian Longmaxi Formation.

3. Solving of dynamics prediction model of gas shale

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3.1. Rock dynamics parameter model

Mechanical properties of rock include elastic modulus and rock strength, which reflect the physical properties of rock under external force, and it is the basis of ground stress calculation, borehole stability analysis and fracturing simulation. The core is usually measured in the laboratory under the simulated underground environment, which has high precision but tedious coring work, high cost and low cost performance. Based on physical logging data, the method of mathematical calculation is economical and efficient with accurate data and strong continuity.

3.1.1. Elastic parameters. When the dynamic stress acts on the elastic medium to produce strain, and does not exceed the elastic limitation of the medium, the transfer of stress and strain will occur and produce elastic wave. The propagation characteristics of the elastic wave are related to the dynamic characteristics of rock. According to the theoretical relationships between the velocities of P and S-waves and rock dynamic parameters which are given by the P and S-wave propagation equations, we use Sonic Scanner logging data to get the compressional wave time differences $\Delta t_c$ and shear wave time differences $\Delta t_s$, and use density logging data to get the volume density $\rho_b$ to calculate various rock mechanical parameters:

- Dynamic shear modulus $G_{dyn}$: the ratio of stress to strain when the rock undergoes shear deformation under shear stress.

$$G_{dyn} = \frac{\rho_b}{(\Delta t_s)^2}$$  \hspace{1cm} (1)

- Dynamic volume modulus $K_{dyn}$: the ratio of hydrostatic pressure to volume strain when rock is subjected to uniform static pressure.

$$K_{dyn} = \rho_b \left[ \frac{1}{(\Delta t_s)^2} \right] \frac{4}{3} G_{dyn}$$

$$= \rho_b \frac{3(\Delta t_s)^2 - 4(\Delta t_p)^2}{3(\Delta t_p)^2 (\Delta t_c)^2}$$ \hspace{1cm} (2)

- Dynamic Young modulus $E_{dyn}$: the ratio of tensile stress to tensile strain, corresponding to the tensile stress level of rock.

$$E_{dyn} = \frac{9G_{dyn} \times K_{dyn}}{G_{dyn} + 3K_{dyn}}$$

$$= \rho_b \frac{3(\Delta t_s)^2 - 4(\Delta t_p)^2}{(\Delta t_p)^2 3(\Delta t_p)^2 - (\Delta t_c)^2}$$ \hspace{1cm} (3)

- Dynamic Poisson's ratio $\nu_{dyn}$: the ratio of transverse strain to longitudinal strain, namely transverse compressibility.
4

\[
V_{d_{yn}} = \frac{3K_{dyn} - 2G_{dyn}}{6K_{dyn} + 2G_{dyn}}
\]

\[
= \frac{1}{2} \left( \Delta t_{v} \right)^2 - 2 \left( \Delta t_{h} \right)^2
\]

For the transverse isotropy with vertical axis (TIV) anisotropic formations like shale, we use the Sonic Scanner logging data and adopt the ANNIE hypothesis to obtain the stiffness matrix of anisotropic formation, and then respectively calculate the elastic modulus and Poisson's ratio of the rock longitudinal direction.

\[
\begin{bmatrix}
C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\
C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\
C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & C_{55} & 0 & 0 \\
0 & 0 & 0 & 0 & C_{55} & 0 \\
0 & 0 & 0 & 0 & 0 & C_{66}
\end{bmatrix}
\]

\[E_v = C_{33} - \frac{2C_{13}^2}{C_{11} + C_{12}} \]

\[E_h = \frac{(C_{11} - C_{12})(C_{11}C_{33} - 2C_{13}^2 + C_{12}C_{33})}{C_{11}C_{33} - C_{13}^2} \]

\[v_v = \frac{C_{13}}{C_{11} + C_{12} \frac{C_{13}^2}{C_{11}C_{33} - C_{13}^2}} \]

\[v_h = \frac{C_{33}^2 - C_{13}^2}{C_{13}C_{11} - C_{13}^2} \]

Where, \(E_v\) is dynamic vertical Young modulus, \(E_h\) is dynamic transverse Young modulus, \(v_v\) is dynamic vertical Poisson's ratio and \(v_h\) is dynamic transverse Poisson's ratio.

The dynamic mechanical parameters of rock refer to the mechanical characteristic parameters of rock under various dynamic loads or periodic loads (such as sound waves, shock, vibration, etc.). The mechanical parameters of rock under static loads are static parameters. Borehole deformation and failure is a relatively slow static process. The experimental results show that the dynamic and static parameters of a complete and compact rock are close to each other. However, in the actual stratum, the dynamic and static parameters of rock may vary greatly under the influence of fractures, holes, layers and other factors. In general, dynamic parameters are greater than static parameters. As is seen from the logging curves used in rock mechanics analysis in figure 2, the transverse shear modulus of some well sections is significantly higher than that of the vertical shear modulus, which indicates the existence of anisotropy in rock strata.

3.1.2. Strength parameters. The strength parameters of rock mechanics include uniaxial compressive strength (UCS), friction angle (FANG) and tensile strength (TSTR). These parameters are usually calculated from well logging curves. The strength parameter results calculated as figure 3 show that the strength (UCS) of rock in the reservoir and overlying mudstone layer is relatively constant, but the strength of lower carbonate is very high, reaching 225MPa, which is equivalent to the strength of many igneous rocks.
3.2. Ground stress
As the natural internal stress of materials in the crust, the ground stress is mainly caused by the tectonic movement in the crust, the weight of rock mass, the variation of geothermal energy and the rotation speed of the earth, etc., and it is not disturbed by engineering. It affects the mechanical properties of underground medium and the stability of borehole wall in drilling engineering. The magnitude and direction of tectonic stress in oil and gas accumulation zones are closely related to drilling and exploitation. Using the ground stress state to identify the characteristics of borehole wall can effectively reduce or avoid the drilling accident rate and serve as the basis for the calculation of formation collapse pressure and the evaluation and prediction of borehole wall stability.

The underground geological conditions are unknown and complex, the heterogeneity is outstanding, and the stress states of each point in the geological body are different. It is generally considered that ground stress mainly consists of rock pore pressure, overburden rock pressure and tectonic stress.

3.2.1. Pore pressure. The purpose of pore pressure evaluation is to determine the pressure on the fluid in the formation pores at different depths. The drilled well is usually measured by repeated formation tester (RFT) or modular dynamic tester (MDT), and can be also acquired by well testing. Although the points of the equivalent mud density during drilling overflow are few and scattered, it is more direct and reliable for evaluating pore pressure. In under-compacted sandstone and mudstone profiles, we can establish a continuous pore pressure profile based on well logging or seismic data with the
derivation and operation of compaction theory. According to compaction theory, the acoustic time difference of mudstone decreases with the increase of depth under normal pressure gradient. For normally compacted formation, there is a normal compaction trend line. When the time difference deviates from this normal trend line, it usually indicates an abnormal pressure. For this well, the drilled rock is compact shale and carbonate rock, and the trend line method cannot determine the pore pressure. For these formations, the pore pressure needs to be determined by direct measurement.

3.2.2. Overlying pressure. The overlying pressure is the sum of the gravities of the overlying strata and the pore fluid. Currently, it is generally obtained from the formation volume density (cable logging or core sample) and burial depth through integral calculation, which is seen in Eq. (10).

\[ \sigma_z = \int_0^z \rho_z \cdot g \cdot dz \]  

(10)

Where, \( \sigma_z \) is overlying stress, \( \rho_z \) is density logging value, \( g \) is gravitational acceleration, and \( z \) is buried depth.

In addition, when the logging quality is poor or the density logging of layer is directly missing, we can use the exponential relationship between density and depth (seen in Eq. (11)) to calculate:

\[ \rho_z = \rho_{sur} + A_o (TVD - AG)^a \]  

(11)

Where, \( \rho_{sur}, A_o \), and \( a \) are parameters, \( TVD \) is true vertical depth, \( AG \) is drilling floor height from the ground.

3.2.3. Horizontal ground stress. The ground stress \( \sigma \) can be derived from the hydraulic fracturing method, which utilizes the status of borehole stress and the principle of rock fracture. The minimum horizontal principal stress \( \sigma_h \) at a certain depth can also be directly measured by a loss-loss test (XLOT), micro-fracturing or MDT logging. Based on above, we can calculate the value of principal ground stress calculated by using density logging curves and \( \sigma_z \). Note that, the maximum horizontal principal stress \( \sigma_H \) cannot be directly measured. After calculating the minimum horizontal principal stress by means of the logging data, we can use the borehole image and rock failure model to roughly calibrate the size of \( \sigma_H \). By adopting the porous elastic model, we calculate its principal stress respectively by using isotropic and anisotropic methods. Moreover, the isotropy is calculated by Eq. (12), and the anisotropy is calculated by Eq. (13).

\[ \sigma_h - aP_p = \frac{\nu}{1-\nu} \left( \sigma_v - aP_p \right) \]  

(13)

\[ \sigma_h - aP_p = \frac{E}{1-\nu^2} \varepsilon_h + \frac{E_v}{1-\nu^2} \varepsilon_H \]

\[ \sigma_h - aP_p = \frac{E_{harz}}{1-\nu_{harz}} \cdot \frac{v_{vert}}{1-\nu_{harz}} \left( \sigma_v - aP_p \right) \]  

(14)

\[ \sigma_h - aP_p = \frac{E_{harz}}{1-\nu_{harz}} \varepsilon_h + \frac{E_{harz}}{1-\nu_{harz}} \varepsilon_H \]

Where, \( \sigma_h \) is minimum horizontal principal stress, \( P_p \) is pore pressure, \( a \) is Biot coefficient, \( \nu \) is isotropic static Poisson's ratio, \( E \) is isotropy Young modulus, \( \varepsilon_h \) and \( \varepsilon_H \) are tectonic stress coefficients, \( v_{harz} \) and \( v_{vert} \) are static Poisson's ratios in horizontal and vertical directions of anisotropic respectively, \( E_{harz} \) and \( E_{vert} \) are static Young moduli in horizontal and vertical directions of anisotropic respectively.

4. Result Analysis

4.1. Evaluation of rock compressibility
After the rock mechanics model is verified, we analyze the compressibility of the horizontal well section according to the previously determined static Young modulus, Poisson's ratio and the minimum horizontal principal stress. As is seen from the figures, the reservoir has relatively high compressibility, and the minimum horizontal principal stress is lower than that of the overlying strata and lower carbonate, which indicates that the completion quality of this well section is relatively high.

4.2. Analysis of rock mechanics parameters

Table 1 below gives a summary of the expected reservoir section, the rock mechanical parameters of overlying strata/bottom layer and the ground stress. From the table, we can see the elastic parameters of the reservoir section of Wei202 Well, where Young modulus is 23.3GPa, Poisson's ratio is 0.17, and minimum horizontal principal stress is 50.6MPa. This is obviously different from the rock mechanics parameters and ground stress of the overlying and underlying strata, which indicates that the fracture boundary conditions are reliable.

Table 1. Summary of rock mechanics parameters and stress in reservoirs.

| Horizon                        | Minimum horizontal principal stress (Mpa) | Poisson’s ratio | Young modulus (Gpa) |
|--------------------------------|------------------------------------------|-----------------|---------------------|
| Overlying strata (2460-2543 m) | 61.2                                     | 0.23            | 28.3                |
| Reservoir (2543-2573 m)       | 50.6                                     | 0.17            | 23.3                |
| Bottom layer (below 2573 m)   | 65.6                                     | 0.26            | 46.2                |

5. Conclusions

(1) Significant wellbore collapse occurs in well section, which indicates that the maximum and minimum horizontal principal stresses in a specific location are quite different. This is conducive to the generation of artificial fractures; however, the large horizontal stress difference coefficient is not conducive to the formation of complex network fractures.

(2) When the in-situ stress of the reservoir section in the target formation is less than that of the upper and lower interlayers, the compressibility index of the reservoir section is higher and the compressibility is better than that of the interlayers. Therefore, the target formation is easy to fracturing and has a better control effect on the height of the accretive fracture.

(3) Through the model prediction, the Young's modulus of reservoir section is 23.3GPa, the Poisson's ratio is 0.17, and the minimum horizontal principal stress is 50.6MPa, which is quite different from the rock mechanics parameters and in-situ stresses of overlying and underlying strata. This shows that the model can predict the boundary conditions for fracture.

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