Modelling igneous rock mechanics parameter based on logging data in Shunbei oil field

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Abstract: In order to improve the rate of penetration (ROP) in Permian igneous rock strata, the rock mechanics is modeled based on the continuous logging data (acoustic, density, caliper, resistivity and gamma logging) and confirmatory indoor experiments. The model considers the influence of well collapse and expansion on logging data in igneous rock formation to improve the calculation accuracy. Based on this model, the continuous profile of Permian compressive strength, tensile strength, mud content, internal friction angle are calculated, and then the differences of Permian strata in the north, middle and south of the oilfield are further compared and analyzed. The results can provide support for the optimization of efficient rock breaking and reservoir fracturing technology.

1. Introduction
Since 2019, Northwest Oilfield has continuously built high-yield wells in the central and southern part of X block in Shunbei oilfield, and further exploration and development of this block is of great significance to achieve the production target of 10 million tons per year. However, the buried depth of the reservoir can exceed 8000m, the average drilling cycle is more than 120 days longer than that in the adjacent block. The investment on well construction is quite too high; and it is in urgent need to improve the ROP in Shunbei oilfield [1-4].

Based on the quantitative analysis of well history data, it is found that early damage of bit in Permian formation leads to frequent tripping and poor drilling effectiveness, in addition to slow ROP. The statistical data also indicate great differences between the northern, central and southern region of the block. Therefore, the rock mechanics is modeled based on the continuous logging data (acoustic, density, caliper, resistivity and gamma logging) and confirmatory indoor experiments, which could facilitate better recognition of the formation and optimization drilling technology accordingly.

2. Calculation model of rock mechanics parameter
The rock mechanical parameters of the formation are the basis for understanding the characteristics of the formation. The main rock mechanical parameters include elastic parameters (Poisson's ratio, elastic modulus) and strength parameters (uniaxial compressive strength, tensile strength, cohesion and internal friction angle). Relying on the continuity, reliability and economic advantages of logging data, many studies have modeled the rock mechanical parameters [5, 6]. The author revised the calculation model according to the characteristics of Permian igneous rock formation.
2.1 Elastic modulus and Poisson’s ratio

According to the elastic wave theory, the calculation model of dynamic Poisson's ratio and dynamic elastic modulus is calculated based on P-wave acoustic logging data and density logging data [7-9]:

\[
\mu_d = 0.5 \times \frac{(\Delta t_s^2 - 2\Delta t_p^2)}{(\Delta t_s^2 - \Delta t_p^2)} \quad (1)
\]

\[
E_d = \rho_{ma} \times \frac{(3\Delta t_s^2 - 4\Delta t_p^2)}{[\Delta t_s^2 (\Delta t_s^2 - \Delta t_p^2)]} \quad (2)
\]

Where, \(\mu_d\) and \(E_d\) are dynamic Poisson's ratio and dynamic elastic modulus respectively. \(\Delta t_p\) and \(\Delta t_s\) are P-wave acoustic time difference and S-wave acoustic time difference respectively. \(\rho_{ma}\) is density logging data, representing rock skeleton density. The dynamic rock elastic parameters can be fitted into static data through experiments. It is found that the porosity of rock is an important factor affecting the dynamic and static fit. The conversion empirical formula of dynamic and static elastic modulus and Poisson's ratio can be expressed in the following form [10]:

\[
E_s = (m \times \phi + n) \times E_d \quad (3)
\]

\[
\mu_s = \mu_d / (X \phi^2 - Y \phi + Z) \quad (4)
\]

where, \(m, n, X, Y, Z\) are fitting coefficients, dimensionless.

2.2 Rock strength parameters

In igneous rock formation, borehole diameter could expand due to wall collapse, and then borehole expansion will affect the accuracy of density and acoustic logging data. Firstly, the expanded well section is selected according to the well diameter measurement data. Then, the resistivity data is used to fit the acoustic logging data based on gardener formula in the expanding well section. Thirdly, the improved acoustic logging data and resistivity data are used to fit the density logging data. Finally, the rock mechanical parameters are calculated based on the improved acoustic logging data. The compressive strength formula of igneous rock can be calculated based on dynamic elastic modulus and mud content:

\[
\sigma_c = aE_d \left( 1 - V_{cl} \right) + bE_d V_{cl} \quad (5)
\]

Among them, the mud content is calculated based on gamma logging data:

\[
I_{GR} = \left( GR - GR_{min} \right) / \left( GR_{max} - GR_{min} \right)
\]

\[
V_{cl} = (2^{0.7 \times I_{GR} - 1}) / (2^{3.7} - 1) \quad (6)
\]

The internal friction angle of rock is calculated based on the dynamic elastic modulus, and its formula is:

\[
\theta = 2 \times \left( 1 - \mu_d / (1 - \mu_d) \right) \times \pi / c \quad (7)
\]

In formula(5) ~ (7), \(a, b, c, d, e\) are fitting coefficients, dimensionless. Through indoor experiments, the specific value of fitting coefficient is determined.

3. Results and discussion

Fig. 1 presents the rock compressive strength profile of Permian strata in the north region of X block in Shunbei oilfield. It can be seen that there are mainly two sections of igneous rocks in the stratum. The thickness of the upper dacite is about 100m, and the compressive strength fluctuates in the range of 140-160MPa, which is the first strength crest. The second igneous rock is mainly composed of 160m dacite and 30m basalt. The compressive strength increases to 150-170MPa, which is the second strength crest. 50m thick calcareous mudstone is sandwiched between the two igneous rocks, which is the first strength trough. The lower part of Permian is tuff with low rock strength. On the whole, the strength of Permian rocks fluctuates greatly, which tends to induce bit collapse. In addition, the polynomial fitting function of rock compressive strength to well depth is also given in the figure, so as to facilitate the subsequent prediction of rock strength before drilling.
Fig. 1 shows the compressive strength profile in the northern region. Fig. 2 and Fig. 3 respectively show the variation profiles of Permian compressive strength with well depth in the central and southern region. The comparison shows that, there are generally three sections of Permian igneous rocks in the central region, and the distribution of igneous rocks in the southern region has strong randomness. From north to south, the buried depth of Permian system shows a decreasing trend, the average strength of igneous rock decreases, and the proportion of igneous rock strata in Permian system decreases, but the characteristics of soft hard crisscross gradually increase.

Fig. 2 shows the compressive strength profile in the central region.
Taking the central region as an example, figure 4 and figure 5 show the calculation results of mud content and internal friction angle of Permian strata respectively. The average mud content of Permian is about 12%, and the average internal friction angle exceeds 50°; The friction angle and mud content of Permian formation are significantly higher than those of adjacent formation. Overall, the Permian igneous rock formation are difficult to drill with strong heterogeneity, high rock strength and strong abrasiveness.
4. Conclusion

In this study, the igneous rock mechanical parameters is modeled based on the logging data, and the continuous profile of compressive strength, mud content and internal friction angle are calculated in the Permian formation. The following conclusions are obtained:

(1) The average mud content of Permian in block X of Shunbei oilfield is about 12%, and the average internal friction angle exceeds 50°; the Permian igneous rock formation are difficult to drill with strong heterogeneity, high rock strength and strong abrasiveness.

(2) There are generally two section of igneous rocks in the Permian in the northern region, and three section in the central region. The distribution of igneous rocks in the southern region has strong randomness. From north to south, the buried depth of Permian system shows a decreasing trend, the average strength of igneous rock decreases, and the proportion of igneous rock strata in Permian formation decreases, but the characteristics of soft hard crisscross gradually increase.

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