The Calculating Method of Rock Compressive Strength Based on Logging Data

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Abstract. Rock compressive strength was a basic lithomechanics parameter. And rock compressive strength affected the drilling ability and stability of rock in drilling engineering. So a calculating method of stratum rock compressive strength was needed to raise the reliability of stratum information acquired. Then the bit selection, well design and reservoir stimulation design could be more accurate. By analyzing the experiment data of rock 3-axis compressive strength, a logging interpretation method of confining pressure has been established, and by considering the influence of confining pressure, a quantitative calculating method of rock compressive strength based on the logging data has been given. This model was used to analyze an exploration well. The results showed that the rock compressive strength was fit to the drilling time, which indicates that this model may accurately recognize the rock compressive strength in the researched area. The result also showed that confining pressure can strongly influence mechanical properties of formation rocks, so if we analyzed the rock mechanical properties, the confining pressure must be taken into account. Besides the method can calculate rock compressive strength in some old well with regular logging data only.

Keywords: Experiment; confining pressure; compressive strength; log; poisson's ratio; interval transit time; application.

1. Introduction

Rock compressive strength is a basic lithomechanics parameter. The rock compressive strength is closely related to rock drillability, it is also an important factor which affects sediment yield of oil wells, and it is an important parameter for drilling design, bit optimization, reservoir transformation measures and program design (Li Zhiguo and Yang Chunhe, 2009; Yang Jian et.al, 2012; Zhou Wen et.al, 2008; Liu Aiqun et.al, 2015; Zhang Shunyuan et.al, 2016). At present, there are two main methods of researching rock compressive strength: measuring rock samples in laboratory and computing with logging data and laboratory data (Wang Yuan et.al, 2005).

There are two main parameters to evaluate rock compressive strength: uniaxial compressive strength and triaxial compressive strength. Uniaxial compressive strength can not reflect the influence of confining pressure for actual drilling (Shen Haichao et.al, 2015). Triaxial compressive strength is mostly obtained by experiment, and there is little calculation method of actual rock compressive strength under confining pressure. Therefore, a logging interpretation method of confining pressure of formation rock is established by theoretical analysis. By analyzing experimental triaxial compressive strength data, the calculating model of rock compressive strength considering the influence of confining pressure is obtained. Finally the calculation model of actual rock compressive strength based on logging data is established.
2. Model of Triaxial Compressive Strength of Rock

Some empirical relationships between uniaxial compressive strength and elastic modulus of sedimentary rocks have been obtained from accumulated engineering data. So there is a fuzzy positive correlation between uniaxial compressive strength and elastic modulus of rock (Farmer, I.W., 1988; Tang Daxiong and Sun Suwen, 1987). In addition, triaxial compressive strength of rock is directly related to uniaxial compressive strength of rock. Therefore, there is an inherent correlation between rock compressive strength and rock lithologic modulus (Li Yu, 2004).

\[ E = \rho \left( \frac{3 \Delta T_p^2 - 4 \Delta T_s^2}{T_s^2 (\Delta T_s^2 - \Delta T_p^2)} \right) \times \beta \]

\( \Delta T_p \) —— the P-wave interval transit time, \( \mu s/m \);
\( \Delta T_s \) —— the S-wave interval transit time, \( \mu s/m \);
\( \rho \) —— the rock density, g/cm\(^3\);
\( \beta \) —— conversion coefficient.

Therefore, rock compressive strength can be measured by logging parameters, such as interval transit time. According to the relationship between compressive strength and elastic modulus, the interpretation method of rock triaxial compressive strength based on interval transit time is obtained through experiments.

![High temperature and pressure rock triaxial apparatus](image)

Figure 1. High temperature and pressure rock triaxial apparatus.

The triaxial rock mechanics test is carried out by applying equal liquid confining pressure in the horizontal two principal stress directions and mechanical axial pressure alone in the longitudinal direction. The experiment was completed on "High temperature and pressure rock triaxial apparatus". The result shows that rock compressive strength is closely related to rock density, rock porosity and confining pressure. Considering the consistency between conventional logging parameters and laboratory measurement parameters (including triaxial compressive strength, strength, Poisson ratio, modulus of elasticity, interval transit time, etc.), the interval transit time is used as the main measurement parameter. Therefore, ultrasonic testing is carried out simultaneously during the experiment, and finally 12 groups of rock compressive strength and interval transit time test results under confining pressure are obtained (Table 1).
Table 1. Experimental results of rock compressive strength and interval transit time.

| NO | confining pressure MPa | compressive strength MPa | Poisson ratio | modulus of elasticity GPa | interval transit time μs/m |
|----|------------------------|--------------------------|---------------|--------------------------|--------------------------|
| 1  | 10                     | 178.4                    | 0.191         | 26.549                   | 206                      |
|    | 20                     | 208.6                    | 0.194         | 21.286                   | 226                      |
|    | 40                     | 295.1                    | 0.197         | 26.819                   | 287                      |
| 11 |                        |                          |               |                          |                          |
|    | 20                     | 177.8                    | 0.31          | 22.4                     | 264                      |
|    | 30                     | 274.6                    | 0.35          | 23.9                     | 295                      |
|    | 40                     | 321.5                    | 0.36          | 25.9                     | 323                      |
| 12 |                        |                          |               |                          |                          |
|    | 20                     | 265.9                    | 0.2           | 43.59                    | 195                      |
|    | 30                     | 298.8                    | 0.21          | 51.78                    | 204                      |
|    | 40                     | 329.1                    | 0.28          | 57.5                     | 236                      |

By fitting the data in Table 1, the calculation model of rock compressive strength $\sigma_{bc}$ considering confining pressure is obtained.

$$\sigma_{bc} = 368.9e^{-a\Delta T_e + b\Delta P} \quad (2)$$

$\sigma_{bc}$——the compressive strength of rock, MPa;
$\Delta P$——the confining pressure, MPa;
$a, b$—— constant, which is related to lithology.

As showed in formula (1), the compressive strength of actual rock can be characterized by interval transit time, which is mainly affected by lithology and confining pressure. Confining pressure is related to drilling fluid density, depth, rock density, porosity, formation compaction and other factors(Sun Yeheng, 2010). Therefore, the key is to establish a rock confining pressure calculation model based on logging data.

3. Calculation of Confining Pressure

In drilling, the confining pressure exists at bottom, which is determined by formation horizontal stress and formation pore pressure. In drilling conditions, confining pressure related to the minimum horizontal principal stress and pore pressure.

$$\Delta P = \sigma_h - P_p \quad (3)$$

$\sigma_h$——the minimum horizontal principal stress, MPa;
$P_p$——the pore pressure, MPa.

There are many inversion methods for calculating the minimum horizontal principal stress. Pro.Huang's is adopting for calculating in-situ stress(Huang Rongzun and Zhuang Jinjiang, 1986).

$$\sigma_h = \left( \frac{\mu}{1-\mu} + \gamma \right) \sigma + \alpha P_p \quad (4)$$

$\gamma$——constant;
$\sigma$——the effective force, MPa;
$\mu$——Poisson's ratio;
$\alpha$——Biot coefficient (effective stress coefficient).

$\gamma$ is a constant reflecting the magnitude of tectonic stress in horizontal direction, and it is a fixed value for a given area, but it varies with the area.
The commonly methods of calculating pore pressure are the equivalent-depth method, Eaton method and effective stress method (Shi Xian et al., 2006). Referring to Pro. Zhou's (1999) method of calculating overburden strata pressure, the pore pressure should be calculated.

\[ P_v = (P_v - \sigma)/\alpha \]  

(5)

\( P_v \) — the overlying strata pressure, MPa;
So the key is to establish logging interpretation methods for overburden strata pressure \( P_v \), effective stress \( \sigma \) and effective stress coefficient \( \alpha \), in which \( P_v \) can be obtained by density logging data (Fan Honghai et al., 2011; Fan Honghai and Zhang Chuanjin, 2002), \( \sigma \) can be obtained by acoustic logging, density logging and neutron logging data (Wang Tieli and Shi Weibing, 2010; Huang Yan and Zhang Chaomo, 2015), while logging interpretation of \( \sigma \) needs further study.
Reports (Liu Zhidi et al., 2003; Liu Zhidi et al., 2005) show that there is exponential function relationship between effective stress and Poisson's ratio. The Poisson's ratio can be calculated by acoustic logging data. So the effective stress \( \alpha \) can be obtained indirectly by logging data. Referring to the statistical regression relationship between effective stress and Poisson's ratio (Liu Zhidi and Tang Xiaoyan, 2011), the basic relationship between effective stress and Poisson's ratio is constructed. The statistical regression equation between effective stress and Poisson's ratio is obtained by synthesizing the experimental data.

\[ \sigma = P_v e^{\mu} \]  

(6)

\( C \) — constant related to lithology.
According to the theory of rock elasticity, Poisson's ratio can be obtained from P-wave and S-wave logging data.

\[ \mu = \frac{0.5(\Delta T_s / \Delta T_p)^2 - 1}{(\Delta T_s / \Delta T_p)^2 - 1} \]  

(7)

\( \Delta T_s \) — the S-wave time difference, \( \mu s/m \) (Yang Xiujuan et al., 2008)

\[ \Delta T_s = \frac{\Delta T_p}{1 - 1.15 \left( \frac{1}{\rho} + \left( \frac{1}{\rho^3} \right)^{\frac{3}{2}} \right)} \]  

(8)

\( \rho \) — rock mass density, kg/m³.
The model formula (1)~ (7) shows that rock compressive strength is directly related to rock density, rock mechanical properties (Poisson's ratio), rock porosity, formation depth, lithology and other parameters. Therefore, to study the mechanical properties of formation rocks, the calculation model of rock mechanical parameters established by considering only one parameter will inevitably deviate from the actual situation, but the confining pressure is a comprehensive parameter, which can synthesize the above parameters, and can be easily combined with experiment data.

4. Application
Well HS2 is located in the Piedmont structural zone of Junggar Basin, and its strata are basically in the Permian-Carboniferous of Upper Paleozoic. Its lithology is dense and dominated by large igneous rocks with high hardness, difficult fragmentation and low penetration rate. Laboratory rock mechanics experiments show that the formation has high compressive strength and poor drillability, but limited by the penetration rate and drilling cycle, the formation coring is less, which can not fully reflect the formation. The mechanical state increases the difficulty of speed-up plan formulation. Therefore, compressive strength calculation method based on logging data is used to process the logging data in the range of 90m-2000m in well HS2, and the data processing results are interpreted.
The downhole rock compressive strength distribution profile is established, as shown in Fig. 2. The calculation method and the calculation method in reference (Liu Aiqun et.al, 2015) are compared, as shown in Fig. 3.

![Figure 2. Compressive strength profile of HS2 well.](image)

![Figure 3. Comparison of results of calculation method and method in reference.](image)

The compressive strength of rock increases with the well depth (as in Fig. 2). This is mainly due to the rock compaction increases with well depth, the energy required to destroy rock increases due to the confining pressure. Therefore, to increase the penetration rate, not only increase the energy supply, but also change the stress state and rock breaking mode. Then reducing confining pressure or even underbalanced drilling technology can be used to change the stress state of rock. And impact effect such as air hammer, torsional impact tool, etc can improve instantaneous rock breaking energy. It shows that rock compressive strength has a good correlation with drilling time (as Fig. 2). Drilling time becomes slower as the rock compressive strength increase. The air drilling method is adopted in the 90m-375m section and the compressive strength is relatively low (80 MPa-140 MPa), so the average drilling time is about 30 minutes, while the later gas change to drilling fluid, the formation
compressive strength increases continuously (from 100 MPa at 400 m to 180 MPa at 2000 m), and the drilling time increases from 40 min to 100 min, which shows that this method can reflect the real formation compressive strength.

Fig. 3 shows that (Liu Aiqun et al., 2015) use the interval transit time as main evaluation method, and use the well depth as main influencing factor, the rock compressive strength is quite different from the laboratory test results in Table 1, due to the single consideration factor. For example, the confining pressure is 10 MPa at 1509 m, the interval transit time is 208 μs/m. Compressive strength is about 178 MPa according to the experimental results in Table 1. Compressive strength calculated by the method described in reference (Liu Aiqun et al., 2015) is only 134.1 MPa. The calculated value of the established method is 179.1 MPa, with a difference of 45 MPa. The main reason for the difference is that the calculation method in the literature simply regards hydrostatic pressure as confining pressure, thus confining pressure becomes a single factor function of well depth, which is inconsistent with the actual situation of formation. Therefore, the confining pressure of actual formation rock is affected by many factors, so many factors must be taken into account in calculating and interpreting the mechanical parameters of formation to improve the prediction accuracy.

5. Conclusion
(1) Based on the analysis of experimental data, the method takes interval transit time as the main identification method of rock compressive strength, and takes the influence of confining pressure into account, so as to improve the accuracy of calculation.
(2) Application shows that the calculation results of this method are in good agreement with drilling time and laboratory test results, which proves that this method is an effective method for calculating the compressive strength of underground rock.
(3) The method uses conventional logging data to calculate compressive strength, which provides a new idea for the analysis of formation rock mechanics characteristics of some old wells with conventional logging data.
(4) This method uses data regression to establish the numerical relationship between compressive strength and confining pressure, which lacks the corresponding theoretical basis. Further research is needed in this direction.

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