Abrasiveness evaluation of complex strata based on PDC special energy consumption

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Abstract

The rock abrasiveness is determined with various methods, which results in no uniform standard formed. In order to predict the PDC bit wear and the abrasiveness of complex strata, the force analysis of the PDC broken rock was carried out, and the bit axial load and torque were obtained, respectively. Then, the calculation model of PDC special energy consumption is deduced. Combining the typical distribution patterns of different strata, the specific energy prediction model of complex strata is established. The wear coefficient of PDC is obtained by the relationship between the triaxial compressive strength of rock and the specific energy of rock breaking, and the grading coefficient and grading standard of abrasiveness of the composite formation are derived, which led to the grading coefficient and grading standard of complex strata abrasiveness. The field test of a well in the north of Songliao Basin verified the rationality and effectiveness of the abrasiveness grading standards and provided the basis for the selection and design of the bit.

Keywords Wear · PDC · Special energy · Complex strata · Rock fragmentation

Introduction

The use of polycrystalline diamond compact (PDC) bit is very versatile in soft to medium hardness formations (Zhu et al. 2013; Wang et al. 2017). The drillability of rock is usually used as an indicator for PDC bit selection and design (Yarali and Kahraman 2011), but the degree of PDC bit wear is often overlooked, which results in a mismatch between the selected bit and the formation. The PDC bit will be worn out while breaking the rock, which can cause the bit to fail (Yahiaoui et al. (2013)). The ability of the rock to wear the drill bit is defined as the rock abrasiveness (Thuro and Käsling 2010). However, due to the complexity of the problem, there is still no universally accepted determination method and grading index of rock abrasiveness in oil drilling formations (Tanaino 2015; Oparin and Tanaino 2015). The specific energy consumption of rock broken by the PDC bit can reflect the downhole working conditions and the wear of the

drill bit (Atici and Ersoy 2009). Therefore, the PDC specific energy consumption can be used to predict the distribution of the abrasiveness of the drilled strata.

At present, the study of the rock abrasiveness is usually the use of laboratory experiments to measure the amount of wear of the drill bit, and then a corresponding regression model is established. This method has many disadvantages such as complicated operation, high cost, and poor versatility. Many authors aimed in their research according to the special energy theory to find the best optimum method to detect the wear of the drilling bits and how to evaluate the rock abrasiveness to avoid the consequent problems that might occur due to worn bits. Pessier et al. (Pessier and Fear 1992) analyzed the wear of the drill bit during the drilling process based on the specific energy consumption of the drill bit and conducted a trend analysis of the wear of the drill bit through the mechanical specific energy trend line. Waugham et al. (2003) established a real-time mechanical specific energy monitoring system, which can detect PDC bit wear as early as possible. Dupriest and Koederitz (2005) plotted the relationship between bit energy consumption and well depth to determine when the drill bit was worn out. Rafid et al. (2014) used a modified technique based on combined bit dullness and specific energy as trending tools for determining the status of the drill bit even in cases where

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drill torque data are unavailable. However, most of the above research methods on the wear phenomenon of the drill bit are limited to the trend analysis and the amount of wear on the bit cannot be accurately quantified. In addition, many strata encountered by the PDC are complex strata. So the heterogeneity of the rock has a great influence on the wear of the PDC bit and the abrasiveness of the strata.

In this paper, based on mechanics analysis of PDC drilling process combining with the calculation model of special energy of complex strata, a method of evaluation of strata abrasiveness is proposed, which can fundamentally solve the disadvantages of lag and the high cost of traditional laboratory test methods. Drillability determines the difficult degree with which the drill bit breaks the rock and the abrasiveness reflects the rock's ability to wear the bit. Only when the two are combined can the bit selection and design be better.

PDC bit mechanical analysis

Single PDC cutter force

The main way for PDC bit to break rock is shearing (Lin et al. 1992). The resultant force is synthesized by the force of each cutter. So the research of the stress of a single cutter is the basis for the performance analysis of PDC bit. Figure 1 shows the force of a single PDC cutter breaking the rock. The axial load and horizontal load of the bit acting on a single PDC cutter are F_n and F_r respectively. F_N is the reaction force of the rock to the PDC when a single PDC cutter presses vertically into the rock at a certain depth d . P_N is the reaction force of the rock to the PDC when the PDC horizontal cutting produces a certain limit displacement to reach the rock breaking condition. F_s

Fig. 1 Single PDC cutter force diagram

is the horizontal friction between the bottom of the PDC and the rock. θ is the PDC negative rake angle; l is the cylindrical maximum contact length. Rock broken by PDC cutter can be decomposed into two processes (Germay et al. 2009): vertical compression and horizontal cutting. In order to simplify the calculation, the vertical press-in process is also divided into two parts: One part can be regarded as a cylindrical surface contact under the action of pressure F_{N1} , and the other part is considered as a flat indenter contact under the action of pressure F_{N2} . When the PDC cutter is pressed into the rock only by the normal load F_{N1} , there are sliding friction forces F_{s1} and F_{s2} on the contact surfaces of the two sides due to relative sliding, and the friction coefficient is f . So F_N is the resultant force of the F_{N1} , F_{N2} , F_{s1} and F_{s2} in the vertical direction.

$$F_N = F_{N1}(\cos \theta + f \sin \theta) + F_{N2}(\sin \theta + f \cos \theta). \quad (1)$$

Based on the finite element theory, Tianjun (2012) analyzed the stress of PDC broken rock and obtained the formulas for F_{N1} and F_{N2} as follows:

$$F_{N1} = \frac{11E \cdot d^2}{16(1 - \mu^2) \sin 2\theta} \quad (2)$$

$$F_{N2} = \frac{1.015E \cdot d}{(1 - \mu^2) \cos \theta} \cdot \sqrt{\frac{A}{\pi}} \quad (3)$$

where E and μ are elastic modulus and Poisson ratio of rock, respectively; A is the area of the contact surface in the F_{N2} direction.

$$A = \frac{\pi d}{2 \sin \theta} \sqrt{\frac{r \cdot d}{\sin \theta}} \quad (4)$$

where r is the radius of a single cutter.

When the displacement of the horizontal movement of the PDC is s , according to the relationship between the contact stiffness and the contact pressure, the contact pressure at the contact surface is:

$$P_N = \frac{2.03E \cdot s}{1 - \mu^2} \cdot \sqrt{\frac{A \cdot \cos \theta}{\pi}}. \quad (5)$$

The friction F_s between the bottom and the rock can be obtained as follows:

$$F_s = f \cdot F_N. \quad (6)$$

Therefore, according to the equilibrium conditions of the force shown in Fig. 1,

$$F_n = F_N \quad (7)$$

$$F_r = P_N - f \cdot F_n \quad (8)$$

Entire PDC bit force

The installation position of the PDC compact is different, so the depth of cut into the rock is also different during drilling (Sun et al. 2016). As shown in Fig. 2, the PDC surface is considered as N circles of width r so that the forces applied to each of the cutters in one of the rings are the same. The normal pressure F_{ni} and the cutting force F_{ri} of a single cutter on the i th circle are obtained by simultaneous Eq. (1–8):

$$F_{ni} = \frac{E}{1 - \mu^2} \left(\frac{11d_i^2 (\cos \theta + f_i \sin \theta)}{16 \sin 2\theta} + \frac{1.05d_i}{\sin \theta} (\sin \theta + f_i \cos \theta) \sqrt{\frac{A_i}{\pi}} \right) \quad (9)$$

$$F_{ri} = \frac{E}{1 - \mu^2} \left\{ \left[\frac{11d_i (\cos \theta + f_i \sin \theta)}{16 \sin 2\theta} + \frac{1.015}{\sin \theta} (\sin \theta + f_i \cos \theta) \sqrt{\frac{A_i}{\pi}} \right] f_i d_i + 2.03 \sqrt{\frac{A_i \cos \theta}{\pi}} s_i \right\} \quad (10)$$

where d can be calculated based on drilling parameters.

$$d_i = \frac{60v}{N_i n \cos \varphi_i} \quad (11)$$

where φ_i is the angle between the normal direction of the compact press-in and the axial direction of PDC; N_i is the number of i th circle compacts; r_i is the distance of the i th circle compact to PDC axis; v is the penetration rate; and n is the rotational speed.

Assuming that both the axial load Th and the torque Tor on the PDC are borne by the compact, it can be obtained:

$$Th = \sum F_{ni} \cos \varphi_i \quad (12)$$

$$Tor = \sum F_{ri} r_i \quad (13)$$

Fig. 2 PDC load diagram

Special energy consumption of PDC bit in complex strata

Specific energy calculation model

Specific energy is defined as the energy consumption of PDC bit cutting unit volume of rock (Acaroglu et al. 2008), which is determined by the bit of cutting performance and rock properties. According to the definition of specific energy, the PDC specific energy M_{SE} can be calculated by Formula (14):

$$M_{SE} = \frac{Es}{V} \quad (14)$$

where Es is the total energy consumed by the PDC broken rock; V is the volume of the broken rock.

PDC specific energy consumption includes two parts (Huang et al. 2006; Ersoy 2013): On the one hand, the PDC is pressed into the rock under the action of the weight-on-bit resulting in a certain depth of indentation. On the other hand, the rocks are sheared and broken due to rotational movement. Therefore, the total energy consumed by the PDC bit can be obtained by the total amount of vertical work and tangential work.

$$Es = Th \cdot v \cdot t + 2\pi \cdot n \cdot t \cdot Tor \quad (15)$$

The broken rock volume can be obtained from the radius and drilling distance of the PDC bit.

$$V = \pi R^2 \cdot v \cdot t \quad (16)$$

where R is the radius of PDC bit; t is the drilling time.

Specific energy prediction of complex strata

There is no isotropic homogeneous formation in nature (Graziani et al. 2012). There are two or more different formations in the direction of the contact surface of the PDC bit broken rock and drilling extension, and the geotechnical mechanics, engineering geology and hydrogeology of these formations are quite different (Zhu et al. 2012). The combined formations are defined as complex strata. As shown in Fig. 3, it is assumed

Fig. 3 Stratigraphic distribution of PDC contact surface

that the PDC bit surface is in contact with two types of strata. The angle between the boundary of strata I and the center of the drill bit is γ , so as to determine the variability of the strata encountered in the whole well.

The central angle γ is constantly changing in the actual drilling process. In order to simplify the above model, the surface of the drilled strata is equally divided into four parts with a height h , which are the upper part, the middle-upper part, the lower-middle part and the lower part. Therefore, the central angle γ can divide the strata into four typical distribution forms with the height Δh change of the boundary of the two types of strata, as shown in Table 1.

As shown in Fig. 4, only two types of strata combinations are considered. In the l -length wellbore, the whole well section is divided into seven sections according to the distribution of the PDC bit surface contact with the strata. Therefore, the section of the i th interval is:

$$\cos\left(\frac{\gamma_i}{2}\right) = \frac{R - \Delta h_i}{R} \quad (17)$$

where Δh_i is the thickness of strata I in contact with the PDC in the i th interval.

Therefore, the specific energy prediction model of complex strata can be expressed as:

$$M_{SE} = \frac{\sum_{i=1}^k \sum_{j=1}^m (Th_{ij} \cdot l_i + \gamma_{ij} \cdot Tor_{ij} \cdot n \cdot t)}{\pi R^2 l} \quad (18)$$

Fig. 4 The whole well strata variability

where i and j are the number of formations in the complex strata that are divided in the wellbore trajectory direction and the PDC contact surface, respectively.

Evaluation of complex strata abrasiveness

The closer the specific energy is to the compressive strength of the rock, the more efficient the PDC bit is. In 1965, Teale (1965) proposed the concept of minimum mechanical specific energy. He believed that the minimum specific energy should be approximately equal to the compressive strength of rock. However, the PDC drilling is a complicated process and the working efficiency of PDC is only 30–40% (Motahhari et al. 2010). The efficiency of PDC bit breaking rock can be obtained from Formula (19):

$$e = \frac{C_s}{W_f \cdot M_{SE}} \quad (19)$$

where e is the rock breaking efficiency of PDC; W_f is the wear coefficient of PDC; and C_s is the rock triaxial compressive strength, which can be obtained from Formula (20) (Yaralia 2013):

$$C_s = U_{cs} + D_p + 2D_p \sin F_A / (1 - \sin F_A) \quad (20)$$

where U_{cs} is the rock uniaxial compressive strength; D_p is the bottom hole pressure difference; and F_A is the internal friction angle of the rock.

Table 1 Typical distribution of drilled strata

Height Δh	Central angle γ	Partition	Distribution pattern
$0 < \Delta h \leq R/2$	$0 < \gamma \leq 2\pi/3$	Upper part	Typical distribution I
$R/2 \leq \Delta h < R$	$2\pi/3 < \gamma \leq \pi$	Middle-upper part	Typical distribution II
$R < \Delta h \leq 3R/2$	$\pi < \gamma \leq 4\pi/3$	Lower-middle part	Typical distribution III
$3R/2 < \Delta h < 2R$	$4\pi/3 < \gamma < 2\pi$	Lower part	Typical distribution IV

Combine e and W_f into the same coefficient λ to get $\lambda = \frac{C_s}{M_{SE}}$. Then, normalize it to get:

$$\text{Normalized}(\lambda) = 1 - A_f^b \cdot (0 < \lambda < 1) \quad (21)$$

where A_f is the rock abrasiveness coefficient and b is the regression coefficient.

According to PDC bit IADC wear grading (Johnson 2006) standards, the bit wear grade coefficient ΔBG can be determined, which has the following relationship with the rock abrasive coefficient A_f :

$$\Delta BG = 8A_f. \quad (22)$$

Combined with laboratory experiments and logging data, PDC bit wear measured data regression coefficient b was 0.296. As a result, the abrasiveness evaluation model of the complex strata was obtained.

$$A_f = \left(1 - \frac{C_s}{M_{SE}}\right)^{3.4}. \quad (23)$$

There has been no uniform grading standard for rock abrasiveness so far (Almasi et al. 2017), so it is inconvenient for on-site application. According to the abrasiveness index calculation results combined with the traditional grading method using the internal friction angle (Golovanovskiy and Bearman 2008), the rock abrasiveness grading standards were re-established, as shown in Table 2.

Applications

In order to verify the accuracy of the above-mentioned abrasiveness classification, Qian 125-10 Well in the south of Jilin Oilfield Rang 70 block was used as an example to evaluate the complex strata abrasiveness. In this block, it is difficult for the PDC bit to penetrate into the formation at a depth of 1800–2500 m. The footage of a single bit is only 362 m, and the mechanical drilling speed is slow. The hardness and drillability test of the core of this well section found that the

formation is a composite formation with interlaced soft and hard rocks, with many medium-hard rocks, and the hardness distribution is between 335.98 and 1843.46 MPa. The drillability grades of PDC bits all exceed grade 7, mainly concentrated in grades 8 and 10, which are difficult to drill formations. The relevant rock mechanics parameters in the abrasiveness calculation model can be obtained from well logging data of Qian 125-10 Well. The elastic modulus and Poisson's ratio of rock are obtained by Eqs. (24) and (25) (Guo et al. 2012):

$$E = \frac{\rho(3\Delta t_s^2 - 4\Delta t_p^2)}{\Delta t_s^2(\Delta t_s^2 - \Delta t_p^2)} \quad (24)$$

$$\mu = \frac{0.5\Delta t_s^2 - \Delta t_p^2}{\Delta t_s^2 - \Delta t_p^2} \quad (25)$$

where Δt_s and Δt_p are the shear wave slowness and compressional wave slowness, respectively; $\bar{N}_i = (1 + \xi_i \xi)(1 + \eta_i \eta)/4$ is the rock density.

The uniaxial compressive strength, cohesive force and internal friction angle of the rock are regressed through the uniaxial/triaxial compressive strength tests of the rock to obtain a corresponding calculation formula. The corresponding calculation formula for sedimentary rocks is proposed in Eqs. (26)–(28) (Mavko et al. 2020):

$$U_{cs} = 1.13\rho - 7.87E - 2 \times 10^{-4}\rho^2 - 5.5 \times 10^{-3}E^2 + 5.2 \times 10^{-3}\rho E - 1370.46 \quad (26)$$

$$C = 4.69433 \times 10^7 \rho^2 \left(\frac{1 + \mu_d}{1 - \mu_d} \right) (1 - 2\mu_d) \left(\frac{1 + 0.78V_{sh}}{\Delta t_p^4} \right) \quad (27)$$

where C is the cohesive force; V_{sh} is the shale content in the rock; and $V_{sh} = \frac{2^{V_{sh(org)} - G_{CUR}} - 1}{2^{G_{CUR}} - 1}$. Among them, G_{CUR} is the Hilchie indicator and takes 2. $V_{sh(org)} = \frac{GR - GR_{min}}{GR_{max} - GR_{min}}$, GR is the natural gamma value, and GR_{max} and GR_{min} are the maximum and minimum values of the natural gamma.

The internal friction angle of the rock is:

$$\varphi = 2.654 \lg \left(M + \sqrt{M^2 + 1} \right) + 20 \quad (28)$$

where $M = 58.93 - 1.785C$.

According to Eqs. (24)–(28) and real drilling data, a profile of the rock mechanics parameters of the Qian 125-10 Well is shown in Fig. 5.

The abrasiveness coefficient in 1800–2500 m is between 0.4 and 0.5, and Table 2 identifies that the interval belongs to the relatively high abrasiveness strata. According to the actual drilling data of Qian 125-10, the S12516UG PDC

Table 2 Rock abrasiveness grading table

Grade	Abrasiveness coefficient A_f	Abrasiveness
1	<0.1	Low abrasiveness
2	0.1–0.2	Low–medium abrasiveness
3	0.2–0.3	Medium abrasiveness
4	0.3–0.4	Medium–high abrasiveness
5	0.4–0.5	Higher abrasiveness
6	0.5–0.6	High abrasiveness
7	>0.6	Extremely high abrasiveness

Fig. 5 Strata abrasiveness calculation result of Qian 125-10 Well

bit used in this interval has a drilling depth of 469 m, a weight of bit of 100KN, a speed of 42 r/min, a pump displacement of 32 L/s, and a mechanical drilling speed of only 3.29 m/h. After tripping, it was found that the PDC compact had serious abrasion. The comparison photographs of entering and exiting the well are shown in Fig. 6. The IADC wear evaluation of the drill bit is 5-6-WT-A-X-3/16-FC-PR, and the drill bit wear classification coefficient is 3.9, which proves the accuracy and practicality of the above-mentioned rock abrasiveness classification standard. According to the calculation results of the abrasiveness, it is possible to increase the drilling efficiency by replacing the drill bit earlier in the complex strata with high abrasiveness.

Conclusions

By analyzing the rock crushing conditions of the single cutter during drilling, combined with the specific energy consumption of the entire PDC bit in the complex strata drilling and the IADC bit wear classification standard, the following conclusions can be obtained:

- (1) The contact pressure when the PDC bit is pressed into and cut the rock is analyzed, and the force model of the single cutter under rock crushing conditions is obtained. Then, the calculation model of the axial load and torque of the drill bit was established according to the different placement positions of the cutters on the entire PDC bit.
- (2) The stratum in the surface range of the drill bit and in the direction of drilling extension is regarded as non-uniform. The angle between the boundary of different strata and the center of the drill bit is used to determine the variability of the strata encountered in the entire well section. Therefore, the PDC surface contact strata are divided into four typical distribution forms.
- (3) The energy consumed by a PDC bit to cut a unit volume of rock is the specific energy, which is equal to the compressive strength of the rock in an ideal state. Therefore, according to the force model of the PDC bit in the rock breaking process combined with the IADC wear classification standard, the abrasiveness of the rock is reclassified into seven grades.
- (4) The abrasiveness profile of the strata encountered by Qian 125-10 Well was established using the rock abrasiveness evaluation index. The actual drilling data and bit wear conditions verified the reliability of the prediction results.

Fig. 6 Comparison of PDC bit entry and exit

(a) Photo of entering the well

(b) Photo of exiting the well

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