Confined compressive strength model of rock for drilling optimization

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ABSTRACT

The confined compressive strength (CCS) plays a vital role in drilling optimization. On the basis of Jizba's experimental results, a new CCS model considering the effects of the porosity and nonlinear characteristics with increasing confining pressure has been developed. Because the confining pressure plays a fundamental role in determining the CCS of bottom-hole rock and because the theory of Terzaghi's effective stress principle is founded upon soil mechanics, which is not suitable for calculating the confining pressure in rock mechanics, the double effective stress theory, which treats the porosity as a weighting factor of the formation pore pressure, is adopted in this study. The new CCS model combined with the mechanical specific energy equation is employed to optimize the drilling parameters in two practical wells located in Sichuan basin, China, and the calculated results show that they can be used to identify the inefficient drilling situations of underbalanced drilling (UBD) and overbalanced drilling (OBD).

1. Introduction

The confined compressive strength (CCS) is one of the most important parameters for drilling optimization, bit selection, and prediction for the rate of penetration (ROP). A large number of ROP models presented in the literature have considered the effect of the rock strength on ROP such as Bourgoyne and Young's model [1], the roller-cone-bit model presented by Warren [2], and Cunningham's ROP model [3]. In addition, Teale [4] introduced the concept of the minimum specific energy and derived the specific energy equation for rotary drilling. He concluded that drilling attains the highest performance when the specific energy approaches, or is approximately equal to, the compressive strength of the rock to be drilled. Then, the concept of the CCS of rock and the specific energy are employed extensively to optimize the drilling parameters and to assess the bit performance [5–10].

The uniaxial compressive strength (UCS) has been used widely for drilling optimization and ROP prediction for a long time before some drill-bit experts realized that the use of UCS is somewhat problematic because the apparent strength of the rock in the downhole is apparently different from Ref. UCS [6,11–13]. Some researchers discovered that the bit performance is greatly influenced by the differential pressure which is defined as the difference between the borehole and pore pressures. After conducting a laboratory test, they found that the rock strength increases as the differential pressure increases, and ROP decreases as the borehole pressure increases [14–18]. Considering the factors above, Rampersad [11] employed a power function in his CCS model to describe the relationship between the rock strength and the confining pressure, and Caicedo [6,13] proposed a CCS model based on the Terzaghi effective stress principle and Mohr–Coulomb strength theory. The models proposed by the scholars above have a significant effect on engineering, but the lack of consideration of the influence of the porosity on the rock strength and the inapplicability of the Terzaghi effective stress principle to rock limit the utility of these models.
In this paper, a new CCS model is proposed that considers the effects of the porosity and the nonlinear characteristics of the compressive strength as the confining pressure is increased. Moreover, the double effective stress theory is suggested to calculate the confining pressure of the bottom hole.

2. Review of classical CCS models for drilling optimization

The most widely used CCS model is based on the linear rock strength criterion expressed as follows:

$$\sigma_1 = Q + K\sigma_3$$  \hspace{1cm} (1)

where $K$ and $Q$ are the parameters of the material, $\sigma_1$ is the CCS, and $\sigma_3$ is the minimum principal stress.

On the basis of this criterion, Caicedo [6] proposed a model to calculate the rock strength at the bottom of a well, which is expressed as

$$\sigma_1 = UCS + (P_h - P_p) + 2(P_h - P_p)\sin\left(\frac{\phi}{1 - \sin\phi}\right)$$ \hspace{1cm} (2)

where $\phi$ is the rock angle of internal friction, $P_p$ is the pore pressure, and $P_h$ is the mud column pressure.

The linear relationship between the maximum and minimum principal stresses of rock has been widely used in engineering, but it cannot be applied to describe the nonlinear behavior detected by many researchers. As shown in Fig. 1 [19], the fitting results indicate that the strength growth rate decreases as the confining pressure increases; thus, a nonlinear model is available to describe the relationship between the rock strength and the confining pressure.

3. A new CCS model

The porosity of rock not only has a significant influence on the elasticity parameters but also plays an important role in the rock strength. The load-bearing capacity of a rock sample changes as the porosity changes. Nur et al. [20] presented the concept of critical porosity and found that the skeleton barely has any significant carrying capacity when the porosity is greater than the critical porosity, and the fluid is responsible for load bearing. When the porosity is less than the critical porosity, load bearing shifts to skeleton. The test results for sandstone data adopted from Jizba [21] for different porosities are shown in Fig. 2, which clearly shows the nonlinearity in the rock strength for different porosities of sandstone. The value of $\sigma_1 - \sigma_3$ decreases nonlinearly as the porosity of sandstone increases. The relationship between the porosity and the stress deviator of sandstone at different confining pressures can be expressed as

$$\sigma_1 - \sigma_3 = CCS_0 \times \exp(-\phi \times m)$$ \hspace{1cm} (3)

where $m$ is a material parameter, $\phi$ is the porosity, and $CCS_0$ confined compressive strength when the porosity is zero.

The fitting results of the stress deviator versus porosity are summarized in Table 1, and the exponential equation in Eq. (3) can describe this relationship quite well because $R^2$ is relatively high.

Considering the influence of the porosity, an empirical CCS model is proposed for rock subjected to triaxial loads and is expressed as

$$\sigma_1 - \sigma_3 = UCS_0 \left(1 + a\sigma_3^b\right) \times \exp(-\phi \times c)$$ \hspace{1cm} (4)

where $UCS_0$ is the uniaxial compressive strength when the porosity is zero, and $a$, $b$, and $c$ are material parameters.

A particle swarm optimization algorithm [22] was used to obtain $a$, $b$, and $c$, and the results are $a = 0.21$, $b = 0.49$, and $c = 7.63$. Fig. 3 presents the calculated results using Eq. (4) and the strength measured in situ. One can see that the predicted results exhibit great agreement with the measured results.

4. Calculation of the confining pressure at the bottom hole

A laboratory study on the drilling rate of a permeable formation was carried out by Cunningham et al. [14], and a phenomenon in which the drilling rate decreases as the mud column pressure increases was observed. They explained that the
increasing mud column pressure leads to an increase in the rock strength. They also pointed out that the formation pressure (or the pore pressure) was another main factor that influences the drilling rate. As a result, many researchers employed the effective stress theory proposed by Terzaghi [23] to describe the effect of the confining pressure on rock strength, written as

\[ s_{\text{eff}} = \frac{s}{C_0} P_p \]  

(5)

where \( s \) is the total stress.

On the basis of the principle, the difference in the mud column pressure and the formation pressure constitutes the main influencing factor on the drilling rate, and this difference is called the “differential pressure”

\[ P_d = P_h - P_p \]  

(6)

The differential pressure is usually assumed to be approximately equal to the confining pressure of the triaxial strength test by many scholars [6], [12], [13]; however, the bit-tooth penetration test conducted by Maurer [16] challenged this assumption. He concluded that the cater volume decreases by approximately 50% when the borehole pressure is nearly equal to the formation pore pressure from 0 psi to 5000 psi. In other words, the effective stress theory is problematic for calculating the confining pressure of the bottom hole. Practical data from a well located in the Lianhuashan structure of the Sichuan basin also refutes the assumption. In this case, air drilling was applied to a depth from 2500 to 2800 m, and the pore and bottom-hole pressures are 30–32 MPa and 2 MPa, respectively. As a consequence, the differential pressure is –28 to –30 MPa using Eq. (6), which greatly surpasses the tensile strength of sandstone (the tensile strength of most sandstones is less than 20 MPa [24]). Considering above examples, it can be concluded that the assumption cannot be directly used in underbalanced drilling (UBD) and air drilling.

The effective stress of saturated soil calculated by Terzaghi’s expression has enough precision, but it is not suitable in rock mechanics. As shown in Fig. 4, the structure of soil is greatly different from the structure of rock, and the effective stress acting upon the skeleton of soil can be described by Eq. (7). However, for rock material, the total force on an area \( A \) is expressed by \( A \sigma \), and the force of the pore fluid is \( f P_p A \) because the area to which the pore pressure is applied is \( fA \). Then, the effective stress acting on the rock material can be calculated as follows [25]:

\[ \sigma_{\text{eff}}^P = \frac{A \sigma - A f P_p}{A} = \sigma - f P_p \]  

(7)

According to the double effective stress developed by Chuanliang [25], porous media have two types of deformation mechanisms: (1) the deformation of the skeleton grains leads to medium deformation called primary deformation [Fig. 5(a)], and (2) the change in the spatial structure leads to medium deformation called structural deformation [Fig. 5(b)].

Primary deformation can be described by Eq. (7), and the calculated results are called the primary effective stress. As for structural deformation, one can use structural effective stress

\[ \sigma_{\text{eff}}^S = \sigma - \phi_c P_p \]  

(8)

where \( \phi_c \) is the rock contacts porosity, which depends on the degree of cementation. The contact porosity is greater than the primary porosity and smaller than one, i.e., \( \phi < \phi_c < 1 \). For a loose medium, \( \phi_c \rightarrow 1 \), and for dense rock, \( \phi_c \rightarrow \phi \).

The boundary between the permeability and the impenetrability of rock is invalid when the double effective stress theory is adopted because the porosity of rock contributes to the effective stress in Eq. (7) and Eq. (8). Thus, it is more reasonable to calculate the confining pressure of the bottom hole by the double effective stress than Eq. (6). For example, the results calculated from Eq. (6) and Eq. (7) are shown in Fig. 6 when the depth of a well is 3000 m, the porosity is 10%, the density of the formation fluid is 1.0 g/mm³, and the densities of the drilling fluid (\( \rho \)) are assumed to be...
It can be concluded that the differential pressure is negative according to Terzaghi’s expression when the density of the formation fluid is less than that of the drilling fluid; when the density of the drilling fluid is 0.4 g/mm$^3$, the differential pressure is $-18$ MPa, in other words, the rock of the bottom hole was loaded with an $-18$ MPa tensile load. In contrast, the calculated result using the primary effective stress is compressive and equal to 9 MPa. According to the experimental values, the uniaxial compressive strength of rock is 10–15 times its tensile strength, and an $-18$ MPa tension stress does not obviously exist. The double effective stress theory is highly recommended to calculate the confining pressure of the bottom hole for both UBD and overbalanced drilling (OBD), as it can better explain the test data. The value of the differential pressure $P_d$ can be less than zero when the drilling-fluid density is extremely low, such as in air drilling, but it has no significant effect on the rock strength because the value of $\phi P_p$ is small. As a result, UCS can be used in air drilling.

Considering all of the observations and explanations above, the final model for calculating the rock strength of the bottom hole can be written as

$$\sigma_1 = UCS_0 \left( 1 + a (P_h - \phi P_p)^b \right) \times \exp(-\phi \times c) \quad (9)$$

5. Application

Teale [4] presented an equation to calculate the mechanical specific energy for rotary drilling in 1965, expressed as

$$E_s = \frac{W}{A_b} + \frac{120 \cdot \pi \cdot N \cdot T}{A_b \cdot ROP} \quad (10)$$

where $W$ is the weight on the bit, $A_b$ is the borehole area, $N$ is the rotary speed, and $T$ is the bit torque. He found that the minimum specific energy is reached when the specific energy approaches, or is roughly equal to, the compressive strength of the rock to be drilled:

$$E_s = E_{s\text{min}} = \sigma_1 \quad (11)$$

After the concept of the mechanical specific energy was proposed, it has been used to evaluate the drilling efficiency and bit performance [7,9]. According to the theory, $E_s$ is equal to the rock’s compressive strength at perfect efficiency, but the energy for crushing rock is not sufficient when $E_s$ is much greater than $\sigma_1$. The main reasons for this phenomenon are improper drilling operation parameters or drilling problems such as bit balling, vibrations, bit bulling, and bottom-hole balling. In order to calculate $T$ easily, a bit-specific coefficient of sliding friction $\mu$ was introduced to express $T$ as a function of $W$ by Pessier et al. [9]:

$$T = \mu \frac{d_b W}{36} \quad (12)$$

where $d_b$ is the bit size.

The substitution of Eq. (12) into Eq. (10) yields

$$E_s = W \left( \frac{1}{A_b} + \frac{13.33 \cdot \mu \cdot N}{d_b \cdot ROP} \right) \quad (13)$$

Fig. 6. Calculated results using Eq. (6) and Eq. (7).

Fig. 7. $E_s$, $N$, ROP, and $W$ as a function of the depth in the well.

Fig. 8. Founder point of the bit weight.
The field operation and logging data of a well in the western Sichuan basin are employed to calculate $\sigma_1$ and $E_s$ by using Eq. (9) and Eq. (13). The porosity of rock as function of increasing depth was provided by the logging engineer. The pore pressure data were predicted according to Eaton [26]:

$$P_p = \frac{P_{obs}}{C_0} \left( \frac{P_{obs}}{C_0} - P_h \right) \frac{\Delta t_n}{\Delta t_0}$$

(14)

where $P_{obs}$ is the overburden pressure (rocks and fluids), $\Delta t_n$ is the normal sonic travel time, and $\Delta t_0$ is the observed sonic travel time (log data).

UCS is estimated from Ref. [27].

$$UCS = 0.00069 V_p^{1.385}$$

(15)

where $V_p$ is the sonic velocity.

$E_s$, $\sigma_1$, $ROP$, $N$, and $W$ as a function of the depth from 3100 m to 3900 m for rock mainly consisting of sandstones are shown in Fig. 7. The results indicate that both $E_s$ and $\sigma_1$ increase as the depth increases, and $E_s$ is less than $\sigma_1$ when the drilling depth is less than 3460 m. In other words, drilling is efficient. However, $E_s$ is greater than $\sigma_1$ when the drilling depth is greater than 3460 m. This also illustrates that $ROP$ does not always increase as the bit weight increases. When the bit weight increases within region A in Fig. 7, $ROP$ decreases, and $E_s$ increases, which means the energy added by increasing the bit weight is inefficient. The point at which $ROP$ stops increasing as the bit weight increases is referred as the founder point [7]. From Fig. 8, the founder point of the well field test is approximately 250 KN. It can be concluded that the CCS model presented in this article can be used to indicate the inefficiency of a drilling situation and optimize the drilling parameters.

The values of $E_s$, $\sigma_1$, $ROP$, $N$, and $W$ as a function of the depth of another well also located in the Sichuan basin are plotted in Fig. 9. The drilling model is UBD, which differs from previous one, and the coefficient of formation and the mud density are 1.1–1.3 g/cm$^3$ and 1.0 g/cm$^3$, respectively. As shown in Fig. 9, $\sigma_1$ has very little significant variation as a function of depth, mainly owing to the limited depth obtained from field, and the phenomena of decreasing $ROP$ and increasing $E_s$ as the depth increases indicate bit wear or bit balling. $E_s$ is much less than $\sigma_1$ between 2100 m and 2340 m, which means that UBD is very efficient in this formation. However, $ROP$ is comparatively low, and $E_s$ is very high in regions A and B compared to other drilling parameters. Therefore, one can conclude that this phenomenon was mainly caused by the increase in the bit weight and the decrease in the rotary speed. After these parameters were adjusted, the efficiency of drilling greatly improved.

6. Conclusion

1. According to Jizba’s experimental data, a new CCS model considering the influence of the porosity is proposed. The nonlinear feature of the rock strength as the confining pressure increases is accurately described by the model.
2. The double effective stress theory, which treats the porosity as a weighting factor of the formation pore pressure, is introduced to calculate the confining pressure.
3. Combined with the mechanical specific energy equation, the new CCS model can be used to indicate the inefficiency of a drilling situation and optimize the drilling parameters.
4. The proposed model is suitable for both OBD and UBD, and UCS is recommended for use under air-drilling conditions.

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Nomenclature

$a$, $b$, $c$  material parameters
$A$  area of action force
$A_b$  borehole area
CCS  confined compressive strength
CCS$_0$  confined compressive strength when the porosity is zero
$d_b$  bit size
$E_s$  mechanical specific energy
material parameter

N  
rotary speed

K, Q  
parameters of the material

Pp  
pore pressure

P\text{d}  
differential pressure

P_h  
mud column pressure.

P_{\text{obs}}  
overburden pressure (rocks and fluids)

\text{ROP}  
rate of penetration

\text{T}  
bit torque

\text{UCS}  
uniaxial compressive strength

\text{UCS}_0  
uniaxial compressive strength when the porosity is zero

V_p  
sonic velocity

W  
weight on the bit

\sigma  
total stress.

\sigma_1  
maximum principal stress

\sigma_3  
inminimum principal stress

\sigma_{\text{eff}}  
effective stress

\varphi  
rock angle of internal friction

\phi_c  
porosity

\phi  
rock contacts porosity,

\sigma_{\text{p}}  
primary effective stress

\sigma_{\text{c}}  
structural effective stress

\mu_{\text{eff}}  
bit-specific coefficient of sliding friction

\Delta t_0  
observed sonic travel time (log data).

References


