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Original article

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.

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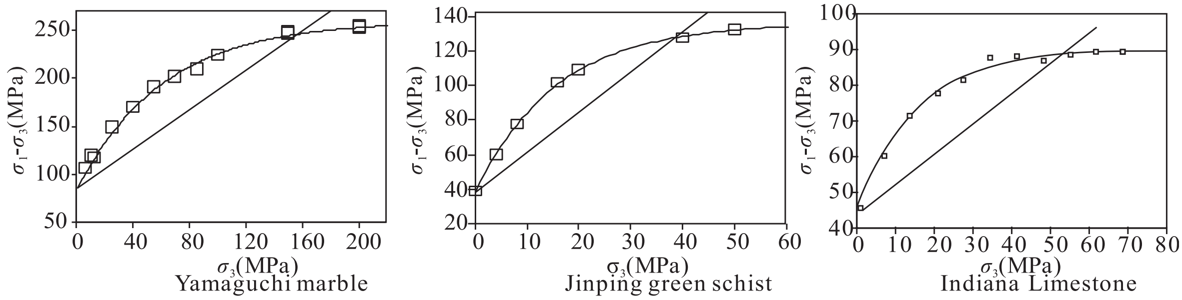

Fig. 1. Fitting curves of the strength and confining pressure for different rock types.

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:

$$\sigma_1 = Q + K\sigma_3 \tag{1}$$

where K and Q are the parameters of the material, σ_1 is the CCS, and σ_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

$$\sigma_1 = UCS + (P_h - P_p) + 2(P_h - P_p)\sin\left(\frac{\varphi}{1 - \sin\varphi}\right) \tag{2}$$

where φ is the rock angle of internal friction, Pp 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

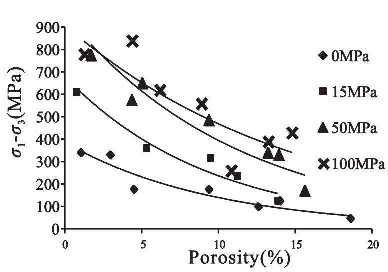

Fig. 2. Porosity versus peak stress at different confining pressures.

$$\sigma_1 - \sigma_3 = \mathrm{CCS}_0 \times \exp(-\phi \times m) \tag{3}$$

where m is a material parameter, ϕ 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

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

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

Table 1
Fitting results of the porosity and differential stress using Eq. (3).

σ_3 (MPa)	Fitting results	R^2
0	$\sigma_1 - \sigma_3 = 385.31\exp(-10.19\phi)$	0.90
15	$\sigma_1 - \sigma_3 = 655\exp(-9.702\phi)$	0.97
50	$\sigma_1 - \sigma_3 = 890\exp(-7.742\phi)$	0.93
100	$\sigma_1 - \sigma_3 = 924\exp(-6.52\phi)$	0.73