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Estimating rock strength parameters using drilling data

Sajjad Kalantari[b,*], Hamid Hashemolhosseini[a], Alireza Baghbanan[b]

[a] Department of Civil Engineering, Isfahan University Of Technology, Iran
[b] Department of Mining Engineering, Isfahan University Of Technology, Iran

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ABSTRACT

Estimating rock strength parameters using operational drilling data can be a fast and reliable method. In this case, several researchers have proposed different analytical models based on force or energy equilibrium methods. Most of them propose methods to estimate uniaxial compressive strength through the investigation of interaction between the bit and rock in drilling process. Although in the proposed models, operational drilling system, rock strength parameters, bit geometry and contact friction were considered, some of the important factors such as crushed zone and its mechanical properties, contact frictions between the bit and rock and friction between the rock and crushed zone need to be explicitly considered. In this research work, a theoretical model is developed based on limit equilibrium of forces and considering contact frictions, crushed zone and bit geometry in the rotary drilling process by a T-shaped drag bit. Based on the model, a method is used to estimate rock strength parameters form operational drilling data. The operational drilling parameters such as thrust force, torque, rate of penetration and speed of rotation were obtained by a developed portable drilling machine. The portable drilling machine is able to drill the rocks with different strength range coincident with measure and record the parameters. A set of drilling experiments were conducted on three different rocks ranged from weak, medium and hard strength. Obtained results based on proposed model for uniaxial compressive strength, cohesion and internal friction angle of rock are well fitted to the results of the conventional standard tests.

1. Introduction

Unconfined Compressive Strength (UCS) of intact rock has been considered as the main parameter in most rock mass classification systems and also as a high limit of the rock mass strength. Determining UCS using suggested standard methods is costly and time consuming mainly due to difficult sample preparation and destructive procedure. Therefore, many indirect methods such as scratch test, point load, Schmidt hammer and punch tests have been proposed for this purpose. Estimating the UCS of rock using drilling parameters is also an alternative method. In this method, continuous measurement of drilling parameters and evaluating of rock strength during the drilling is possible. Beside the advantage of continues measuring, it can be used as a quasi-nondestructive method in field. In large scale, this method can be easily facilitated due to simply movement and no need for sampling. In this case, the drilling methods as well as the bit are most important. Regarding extensive use of rotary drilling systems, it has attempted more attention compared with the other systems and most of the represented methods are accommodated in this drilling system. The drilling process is conducted through two stages of feeding and cutting. At the first stage, the bit indents into the intact rock by the thrust force. As a result of the indentation, a part of rock is crushed and pressed. The compressed crushed zone is formed in front of bit due to the rake angle, cutting face friction and spiral motion of the bit. The next stage of rotary drilling occurs due to the rotational motion of the bit. At this stage, the horizontal force is transferred to the rock along rotating bit but unlike the first stage, the force is transferred to the rock through an intermediary. The intermediary is the compressed crushed zone, which damps a part of the force as frictional one. The crushed zone is more important in investigating the interaction between the bit and rock as well as estimating the strength parameters of rock. This issue, mostly have not been considered in previous proposed models.

According to the literature, previous proposed models which estimate rock strength using drilling technique or propose methods for this aim through the investigation of interaction between the bit and rock is categorized in two forces equilibrium-based and energy equilibrium-based models. The former category has been introduced by Evans[1] as "Indentation Model" which estimates the necessary force to coal plowing. It was also further developed by Nishimatsu[2] as "Shear Model" for estimating the necessary force to shear failure of rock which is based on Merchant's metal cutting Model.[3] There are other models in this category which are developed based on different types of bits such as Detournay et al.[4] and Gerbaud et al.[5], Chiaia,[6] Wojtanowicz et al.[7] or Nakajima et al.[8] models for drag and Polly crystalline Diamond

* Corresponding author.

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Compact (PDC) bits, Franca[9] and Roxborough et al.[10] and Hareland[11] models for roller-cone bits. They proposed relationships between the rock strength parameters and operational drilling parameters based on drilling tools geometry. However except Nakajima et al.[8] and Gerbaud et al. model[5], the effect of crushed zone has not been considered. The Gerbaud et al. model has been aimed to investigate the interaction between the bit and rock in order to increase the efficiency of PDC bits. While compressed crushed zone is the main factor of cutting force transmission from bit to the rock. The energy equilibrium-based methods are adopted from the drilling specific energy, which is initially introduced by Teale[12] and represents the minimum required energy for drilling a unit volume of rock as an index for any type of rock. This amount of drilling specific energy is approximated as UCS of rock. Several researchers[13–22] used different methods to estimate rock strength and bit wearing in rotary drilling by roller-cone, drag and PDC bits based on the drilling specific energy of Teale.[12] The energy equilibrium-based analytical models resolve simply the problem of friction and the crushed zone in drilling process. However they do not propose an explicit relationship between the UCS of rock and drilling parameters. In this case, there is not any specific method for measuring the minimum drilling specific energy.

Detournay and Defourny[4] proposed a method to estimate the minimum drilling specific energy (from cutting point), which is used to estimated UCS of rock in scratch test. This method also can be used as a method to estimate UCS in drilling process. In this research work, a model is developed based on the limited equilibrium of forces in drilling process by a drag bit. In the model, parameters of cohesion and internal friction angle of rock are estimated from operational drilling data and based on these parameters, the UCS of rock is calculated. At the same time, the UCS of rock is estimated from the cutting point. In addition the effects of different parameters on estimated strength properties are also evaluated. A sophisticated drilling machine is developed and operational drilling parameters of three types of rocks with different range of strength from weak in travertine to medium in onyx and high in rhyolite were examined. The machine is able to drill the rocks with different strength range coincident with measure and record the parameters of torque, thrust force, indentation rate, rotation speed and drilling depth via two independent motors. The obtained results from the drilling experiments for strength parameters of rocks have been compared with those results from the conventional standard tests.

2. Developed analytical model

Generally, the rotary drilling process of rock is conducted through two stages. In the first stage, the indentation performs along with axial motion of the bit, which is included the indentation, crushing and smashing. The second stage is the cutting force, which is perpendicular to the axial motion and only cuts the rock. Both stages require to perform the drilling process, since the axial motion of bit needs to keep the cutting depth and feeding and the rotary motion perpendicular to the indentation motion needs to cut the rock. The two stages occur in a continuous and fast process and can be considered simultaneously. The resultant of the two forces have important role. One of the resultant forces functions along the bit axis and the other one is the resultant of forces which are parallel to the bottom hole. The amount and ratio of the two forces in frontal face of the bit mostly depend on the bit geometry especially rake angle and the contact friction. Hereon, the friction force between the compressed crushed particles and rock as well as the bit-end (head) friction affect the forces. Considering the condition, a model is proposed based on the force limit equilibrium in a T-shaped drag bit with negative rake angle, α according to Fig. 1(a) under the atmospheric pressure of drilling process. For a blunt bit, its cross section is rectangular and the area of wearing flat is $l \times D$, where D is bit diameter and l is the width of wearing flat. When the bit is ideally sharp, the width of wearing flat is zero. By helicoidal motion of the bit overcomes the rock strength/resistance and indents into the rock with thrust on the bit. Concurrent with the indentation, the crushed materials are confined and compressed between front face of the bit and rock.

Several factors control the formation of the crushed zone and its compacting in front of the bit. These factors include the rake angle of bit, continuous downward movement of the bit, cutting face friction angle, and the presence of an enclosed space inside the drill hole, which does not allow to move upward the cuttings material from bit in front. In fact, the compressed crushed zone performs as the initial indenter into the intact rock. The compressed crushed zone also transfers a part of the applied forces of bit to the intact rock. In other words as a result of the applied force (F^c) by the bit. The crushed zone transfers some part of the force to the intact rock along the vertical cross-sectional area, which equals the depth of cut multiple bit diameter. The other part of the force transfers to the bottom of hole by compressed crushed zone. Compressed crushed zone is in contact with different strengths of the intact rock and bit. Due to the formation of a compressed crushed zone in front of bit, bit cutting face and rock are subjected to a uniform (hydrostatic) stress (σ_0). The compressive stress in the crushed zone and rock is enough to shearing and chip propagation along linear line. When a sufficient large horizontal force transferred by the compressed crushed zone into the rock, the rock fails with an angle of ψ and chip is formed (Fig. 1(a)). The retention angle (β) of bit is considered as zero to decrease the contact of the bit perimeter (Fig. 1(b)). If bit moves rotationally along cutting direction, the side rake angle (γ) will be zero. Since the hydrostatic condition is dominant in the compressed crushed zone,[5] the amount of the stress would be the same at different directions. The contact friction angle of bit cutting face and bit end wearing face are the same and is considered as θ_f, since both of them have the same material (tungsten carbide), and are in contact with the boundary layer of crashed rock. In this condition, three different media of bit, compressed crushed zone and failed intact rock are in contact.

In *n-t* coordinate system, the force, F_t is acting force in the direction of bit rotation results from bit torque and the force F_n, along the normal axis results from thrust force. Each of the forces has two components; one of which is the cutting force and another one is the frictional force as follows:

$$F_n = F_n^c + F_n^w \tag{1}$$

$$F_t = F_t^c + F_t^w \tag{2}$$

where F_n^c, F_t^c, F_n^w and F_t^w are normal and tangential components of the cutting force, normal and tangential component of the friction force respectively. These parameters are linked with the following relationship,

$$F_n^c = F_t^c \tan(\alpha + \theta_f) \tag{3}$$

$$F_t^w = F_n^w \tan\theta_f \tag{4}$$

$$\tau_0 = \sigma_0 tan\varphi' \tag{5}$$

$$A = dD \tag{6}$$

where α, θ_f, φ', τ_0 and σ_0 are the rake angle, contact friction angle in the bit end wearing face and contact friction angle in bit cutting face, frictional angle between compressed crushed zone and intact rock, shear strength between compressed crushed zone and intact rock, hydrostatic pressure in compressed crushed zone respectively. A, d and D indicate effective vertical cross-sectional area of cut, cutting depth and the bit diameter respectively. It should be noted that for a helicoidal motion of a drag bit, when the drilling is in stationary condition, Eq. (6) is satisfied.[6] Now, considering the compressed crushed zone, we have,

$$F_t^c = A\sigma_0 + A\tau_0 tan\alpha \tag{7}$$

$$F_n^c = A\sigma_0 tan\alpha + A\tau_0 \tag{8}$$

Also in the potentially fail face of wedge, shear, τ and normal, σ tractions are as follow,