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Upper bound analytic mechanics model for rock cutting and its application in field testing

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A B S T R A C T

The rock cohesion *c* and internal friction angle *φ* are essential parameters (combined as the *c-φ* parameter) used to characterise rock strength. Accurate measurement of these parameters is necessary for surrounding rock stability analysis and supporting scheme design in underground engineering. The currently used indoor test procedure is time-consuming and difficult to quantitatively evaluate the mechanical properties of fragmented rocks because these rocks cannot be effectively cored. Most field test methods can measure rock tensile or compressive strength parameters; however, it is difficult to determine the *c-φ* parameter. "Digital drilling rig" test technology provides a new way to solve the aforementioned problem. The key to implement this technology is to create a quantitative relation between the drilling parameters and the rock *c-φ* parameter. In this study, based on the characteristics of the rock cutting failure, an upper bound analytic mechanics model is developed for rock cutting. In this model, the ultimate rock cutting force is derived and the relation between the drilling parameters and the *c-φ* parameter is obtained. A comparative analysis of indoor tests and theoretical calculations shows that the average difference between the drilling parameters from the digital drilling test versus parameters from the theoretical calculation for the limestone tests is 9.33%; for the sandstone tests, the average difference is 5.85%. This validates the rock cutting mechanical model and the formula for the relation between the drilling parameters and the *c-φ* parameter. Based on these results, a digital drilling measurement method for the surrounding rock *c-φ* parameter in the field is proposed. The feasibility and effectiveness of the proposed method is verified via indoor testing. This method is convenient to implement in the field and can effectively measure the *c-φ* parameter of both intact and relatively fragmented rock mass in the field.

1. Introduction

The rock cohesion *c* and the internal friction angle *φ* are the most essential parameters (hereinafter referred to as one combined parameter, the *c-φ* parameter) used to characterise rock strength. Accurate measurement of the *c-φ* parameter is the foundation of surrounding rock stability analysis and supporting scheme design in underground engineering. Conventional *c-φ* parameter measurement methods include indoor testing and field testing. Laboratory triaxial and compression shear test methods can produce accurate results. However, these test methods require the in situ acquisition of rock samples and the transportation of the rock samples to a laboratory for testing; thus, they are time consuming. In particular, the mechanical parameters of the surrounding rock will change when they are disturbed by the excavation activity, and the variation of the mechanical parameters of the surrounding rock will significantly affect its deformation and the mechanical conditions of the support structure. However, laboratory test methods cannot provide a timely evaluation of the variations in the mechanical parameters of the surrounding rock. In addition, it is difficult to quantitatively evaluate the mechanical properties of fragmented surrounding rocks via indoor testing because these rocks cannot be effectively cored and protected during transportation. Therefore, field testing methods have been extensively studied to rapidly determine the *c-φ* parameter. Currently, the main field testing methods are displacement-based back analysis methods (Gioda and Locatelli, 1999; Swoboda et al., 1999; Sakurai, 2003; Feng et al., 2004; Zhang et al., 2006; Yazdani et al., 2012). These techniques determine the rock *c-φ* parameter through back analysis by using an intelligent algorithm

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or numerical simulation based on displacement data on cross-sections that are obtained after underground engineering excavation. Based on previous researches, a method for determining the *c*-*φ* parameters of rock mass by using the "digital drilling rig" test technology is presented in this paper.

A "digital drilling rig" (Suzuki et al., 1995; Gui et al., 2002; Kahraman et al., 2003; Yue et al., 2004; Tan et al., 2005; Yang et al., 2012; Chen and Yue, 2015) is a field survey device that provides accurate control and monitoring of the drilling parameters during drilling. The drilling parameters include the drilling rate, the rotating speed, the torque, the thrust and the specific energy. Research shows that the drilling parameters and the rock mechanical parameters are closely related (Kahraman, 1999; Tan et al., 2007; Yaşar et al., 2011; Aalizad and Rashidinejad, 2012); therefore, finding a quantitative relation between the drilling parameters and the rock mechanical parameters is the foundation of using the "digital drilling rig" to obtain the mechanical parameters of the rock. Numerous researchers have established the relationships of the drilling parameters with the uniaxial compressive strength of rocks (Huang and Wang, 1997; Karasawa et al., 2002; Mostofi et al., 2011; Yaşar et al., 2011) and the structural plane parameters of the rock mass (Schunnesson, 1996, 1998; Akin and Karpuz, 2008; Tan et al., 2009) using statistics, intelligent algorithms and energy analysis methods. However, few studies have investigated the relationships between the drilling parameters and the rock *c*-*φ* parameter, which has limited further development of the digital-drilling-rig-based drilling test technology.

Indoor tests (Chaput, 1992; Richard et al., 1998; Richard, 1999) and numerical simulations (Huang et al., 2013) show that, when the rock-cutting depth of the drill bit cutting edge in a rotation is relatively shallow, the rock fails in ductile mode, i.e., the rock *c*-*φ* parameter controls the rock cutting failure process. Therefore, it is feasible to establish a relation between the drilling parameters and the rock *c*-*φ* parameter based on a mechanical analysis of the rock cutting failure process. Some mechanical models for rock cutting (Nishimatsu, 1972, 1993; Gerbaud et al., 2006; Song et al., 2010) have been developed to investigate the cutting mechanism and optimise drilling tool design. The existing mechanical models for cutting require the assumption of a cutting failure surface shape and the stress distribution. In this study, based on rock cutting failure characteristics, a rock cutting upper-bound analytic mechanics model is proposed. In the proposed model, no assumption for the cutting failure surface stress distribution is required. It provides a more accurate match for the actual failure mode and is applicable in a wider range of scenarios.

In this study, the ultimate rock cutting force is derived and the formula for the relation between the drilling parameters and the c-φ parameter (hereinafter referred to as the DP-CΦ Formula) is developed based on the proposed rock cutting upper bound analytic mechanics model. Indoor testing is performed, using a multi-function true triaxial rock drilling test system developed in-house, to validate the model. Based on the results, the field surrounding rock *c*-*φ* parameter digital drilling measurement method is proposed. The feasibility and effectiveness of the proposed method is verified via indoor testing. This method is convenient to implement in the field and can measure the *c*-*φ* parameter of both intact and relatively fragmented rock mass. The proposed method supports surrounding rock stability analysis and support parameter optimisation in underground engineering.

2. Analysis of the theory of rock cutting

2.1. Mechanism of rock cutting and the basic theoretical assumptions

The rock cutting is performed using conventional polycrystalline diamond compact (PDC) drill bits, wherein the PDCs are embedded in a matrix to form cutting edges that crushes rock, as shown in Fig. 1. The rock is crushed by the cutting edge under the combined effects of the vertical force F_1 and the horizontal force F_2, as shown in Fig. 2. The rock cutting test (Chaput, 1992; Richard et al., 1998; Richard, 1999) and the numerical simulation (Huang et al., 2013) show that when the rock-cutting depth H of the drill bit single-row cutting edge in one rotation increases, the rock failure mode will shift from ductile failure (illustrated in Fig. 2(a)) to brittle failure (illustrated in Fig. 2(b)).

Usually, the width of each row of the cutting edge in the drill bit is more than 10 times H, i.e., H and the rock cutting range L are far smaller than the width of each row of the cutting edge. Therefore, in each cycle of rock cutting, the cutting edge follows an approximately linear path. Because H is usually small, the rock in front of the cutting edge demonstrates mostly ductile failure. The rock cutting problem basically satisfies the conditions of a plane strain problem.

Based on the aforementioned rock cutting failure characteristics and findings from other researchers (Nishimatsu, 1972, 1993; Gerbaud et al., 2006; Song et al., 2010), the following assumptions are made when developing the rock cutting mechanical model:

(1) Because the cutting width far exceeds the cutting depth H, the rock cutting problem is simplified as a plane strain problem.
(2) Because the weight of the rock (gravitational force) in the cutting area is far smaller than the cutting force, gravitational force is not considered in this model.
(3) The rock is treated as an ideal rigid plastic material, i.e., the strain strengthening and softening effects are not considered.
(4) The rock follows the Coulomb yield criteria and satisfies the associated flow rule; and
(5) Rock cutting failure is caused by shear slip along a plane, the rock above the slip surface is treated as a rigid body and deformation is only in a thin failure layer between the virgin rock and the rock chips.

Based on the above assumptions and the rock cutting failure characteristics, a rock cutting mechanical model is developed, as shown in Fig. 3. In the diagram, OA is the cut failure surface, whose angle with respect to the horizontal plane is β; F_c is the cutting force exerted by the cutting edge on the rock in the front; F_f is the force exerted by the cutting edge on the bottom rock; γ is the angle between the cutting force F_c and the normal direction of the surface of the cutting edge; κ is the inclination angle of the cutting edge; δ is the angle between the force F_f and the vertical direction, which is also the friction angle between the cutting edge and the rock; φ is the internal friction angle of the rock; and V is the velocity of the rock chips along the slip surface. Based on the associated flow rule and the Coulomb yield criterion, the angle between the direction of V and the surface of the cut failure is φ (Chen, 1975).

2.2. Analysis of the ultimate rock cutting force

Rock cutting failure is caused by the slip of a plane whose angle with respect to the horizontal plane is β. Based on the ultimate analysis upper bound theory, when the rock fracture power W generated by the cutting force F_c and the cut failure surface energy dissipation rate D are equal, the ultimate condition is met.

The rock fracture power W is the product of the component of the velocity V along the F_c direction and F_c as follows:

$$W = F_c V\cos(\beta + \varphi + \kappa + \gamma) \quad (1)$$

The energy dissipation rate D on the cut failure surface OA is as follows:

$$D = c(V\cos\varphi)\frac{H}{\sin\beta} \quad (2)$$

When the rock reaches the ultimate state, the rock fracture power W and cut failure surface energy dissipation rate D are equal, as follows: