International Journal of Rock Mechanics & Mining Sciences 84 (2016) 80–86

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Technical Note

Numerical simulation of rock cutting in deep mining conditions

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ARTICLE INFO

Article history:
Received 15 May 2015
Received in revised form
7 February 2016
Accepted 14 February 2016

Keywords:
Cutting force
Pick
Deep mining
Finite element
Rock cutting

1. Introduction

In the past decades, many tests have been done here and abroad in attempt to predict pick cutting forces by using mechanical properties of rock, geometrical simplifications and some basic assumptions. Khair[1] developed an automated rotary coal/rock cutting simulator to evaluate the cutting parameters influence on the cutting results. Addala[2] and Liu et al.[3] measured pick cutting forces by cutting tests and investigated the relationship between the cutting parameters and the bit geometry parameters. While the cutting tests provide a reliable method to estimate the tool forces, it takes a long time and expensive process. However, theoretical, semi-empirical, and empirical models can be used to predict tool forces in the absence of experiments.[4] Nishimatsu,[5] Evans,[6] Roxborough et al.[7] and Goktan[8] developed the cutting theory for point attack picks. Although these theories lead to a better understanding of the rock cutting process, they are only moderately effective and pick forces are difficult to estimate due to heterogeneous and anisotropic nature of rocks and three-dimensional asymmetrical attack of point attack pick cutters.[9] To date, the numerical simulations have become easier and faster than experimental methods, and the rock failure process may be traceable in detail by using the numerical methods.[10] Huang et al.,[11] Lei[12] and Rojek[13] developed the distinct element modeling of rock cutting. Okan et al.[14] used the discrete element method (DEM) to model rock cutting tests and pointed out the strong correlation between the modeling, experimental and theoretical studies. Wang et al.,[15] Zeuch[16] and Yu[17] chose the Finite Element Method (FEM) as the simulation tool to model the cutting problem.

Although a considerable amount of literature has been published on numerical modeling of rock cutting so far, there has been no consideration for the effects of the deep mining condition, since it is estimated that 73% of the total reserved coal in China exists at depths greater than 1000.[18] Coal mining in deep dangerous situation may be featured with high temperature, high stress, high karst water pressure and high gas, which will influence the cutting forces severely.

The aim of this paper is to model the rock cutting test in deep mining condition using the Finite Element Method. In order to achieve this aim, explicit time integration and the element erosion algorithm in LS-DYNA3D software were utilized to model the impact between the pick and rock, the results of which were compared with the theoretical model and Okan's results.[14] By using a small single pick cutting test bed as the prototype, a finite element model of a cutting system was established and initially checked with experimental data. Finally, the influence of the lateral pressure in deep dangerous mining condition on the mean peak cutting forces was discussed.

2. Prediction of the cutting force

2.1. Theoretical and DEM models

Evans firstly put forward the cutting theory for point attack

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http://dx.doi.org/10.1016/j.ijrmms.2016.02.003

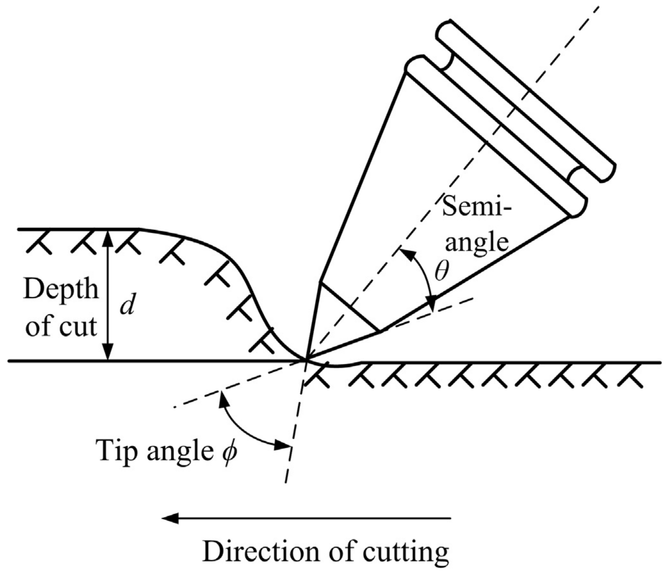

Fig. 1. The cutting parameters of a point attack pick.

picks.[6] He assumed that the picks were rugged and resistant to hard rocks. By neglecting the wear of picks, he proposed that the uniaxial and tensile strength of rock were important for peak cutting forces acting on a conical pick.

$$FC'_{Evans} = \frac{16\pi\sigma_t^2 d^2}{\cos^2(\phi/2)\sigma_c} \quad (1)$$

Goktan[8] modified Evan's theory which did not take the effect of friction angle between rock and tool into account. He overcame the deficiency of Evan's theory that the cutting force did not decrease to zero when semi-angle θ of a pick was zero:

$$FC'_{Goktan} = \frac{4\pi\sigma_t d^2 \sin^2(\phi/2+\gamma)}{\cos(\phi/2+\gamma)} \quad (2)$$

where FC' is the peak cutting force, the subscript of FC' is the researcher's name; σ_t is the tensile strength; d is the depth of cut; ϕ is the tip angle(shown as Fig. 1); $\sigma_c$is the uniaxial compressive strength; γ is the angle of friction between the tool and rock, which is assumed to be 8.5°. Afterward, Okan[14] used the DEM to model rock cutting tests and verified the results with experimental data published by Kel et al.[19] and Bilgin et al.[20]

2.2. The finite element model

As FEM is much more developed and versatile than theoretical models or DEM, we used the FEN approach in our study. LS-DYNA3D is the most well-known commercial software to analyze the dynamic response of three-dimensional solids and structures by using explicit dynamic FEM. In addition, the contact interface capability of LS-DYNA3D to handle the mechanical interactions between the pick and rock is also one of the important reasons for our choice. In this section, we establish a finite element model of the Okan's sandstone-1 model[14] in LS-DYNA3D software.

The sandstone-1 model provided by Okan et al.[14] is mainly composed of a pick and a block of rock. The 3D parametric model of the system was input to the computer and discretized into 8-node hexahedron solid elements. The mechanical properties of materials are listed in Table 1.

In order to treat the dynamic contact between the pick and rock, an algorithm of contact with erosion developed by Belytschko and Lin[21] was chosen, whose purpose was to treat the interaction of two bodies with eroding elements. Then the tensile failure criterion and shear failure criterion were used for the rock material.

During the numerical cutting tests, the bottom and the two sides in x direction of the rock were fixed. Since 30 mm of cutting distance and 0.3 m/s of cutting speed were applied during the modeling studies, the simulation time was 0.1 s. Then the interaction of the rock and pick was monitored. The transient stress nephogram for 3 mm of cutting depth of rock is depicted in Fig. 2. The histories of the tool forces were recorded at frequent intervals such as 10,000 data per second. Hence, the tool forces were measured as sensitively as possible. According to histories of the forces, the mean peak normal forces and the mean peak cutting forces were estimated.

2.3. Comparison of theoretical model, DEM results and FEM results

In order to verify the FEM simulation results, the tool forces of Okan's sandstone-1 model[14] were calculated. The variations of the normal and cutting forces for 3 mm of cutting depth of sandstone-1 are depicted in Figs. 3 and 4. Then the results obtained by FEM, DEM, and theoretical model, given in Table 2, were compared to each other.

As shown in Table 2, for sandstone-1 model, results calculated in this paper agree well with the Okan's solution[14] by using DEM, which indirectly proves the feasibility of the FEM simulation. In terms of theoretical model, the FEM solution is closer to Goktan's model than to Evans's model. Both of the theoretical models fail to account for the influence of the lateral pressure of coal.

3. Numerical modeling of the rock cutting considering with deep mining condition

Deep mining engineering is a current and future problem for most countries in the world. In the major coal mining countries, mining industries of Germany, Britain, Poland, Russia and Japan are relatively developed. The mean mining depths in these countries are listed in Table 3, and the values are increasing at the rate of 8–16 m per year.[22] Along with the growth trend, the mining depth in China is expected to reach 1200 m in 2020.[18] Therefore, it is very important to study the basic theory of mining equipment in deep mining engineering.

Many achievements, which focus on the rock mechanics problems caused by the deep mining engineering, were obtained by scholars through theoretical study, laboratory test and in-site test. However, there have been few studies to estimate the influence of deep mining condition on tool forces. Based on the previous studies of authors,[18,22] the main differences in engineering mechanics for the characters of rock mass between shallow mining and deep mining are summarized as follows: high ground stress, high earth

Table 1
The mechanical properties of the sandstone-1 model cutting system materials.

Material	Modulus of elasticity E (Pa)	Poisson's ratio μ	Mass density ρ (kg/m^3)	Indirect tensile strength σ_t (MPa)	Compressive strength σ_c (MPa)
Pick	2.1×10^{11}	0.3	7800	–	1451
Rock	1.7×10^{9}	0.2	2650	6.6	113.6