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Rock breaking of conical cutter with assistance of front and rear water jet

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ABSTRACT

During the excavation of roadway or tunnel excavation in hard and abrasive rock, the conical cutter is subjected to high cutting forces and serious wear. Therefore, different combinations of water jet and cutter were put forward for this issue, and the damage models of rock breaking with a conical cutter under the assistance of front and rear water jet were established based on the SPH and Lagrange algorithm. By analyzing the dynamic processes of rock breaking with a single cutter under different cutting depths, the cutting force curves were established and compared with the experimental data, the simulation were proved feasible and effective. Then, the effects of rock breaking with the assistance of water jets at different positions and pressures were analyzed, and comparisons were conducted with the effect of rock breaking with a single conical cutter without water jet. The results show that: the numerical cutting force of rock breaking with a single conical cutter coincides well with the theoretical and experimental data. Compared with the peak cutting force of cutter without water jet, the peak cutting force of cutter with the assistance of the front water jet (FWJ) reduces by about 14–30%, and the reduction percentage decreases with the cutting depth, while, the peak cutting force of cutter with the assistance of the rear water jet (RWJ) reduces by about 28–40%, and the reduction percentage is almost not affected by the cutting depth. The effect of rock breaking with the RWJ is better than the FWJ, and the RWJ with the incline angle 5° is the best, the peak cutting force of cutter reduces by about 31%, 39%, 43%, 45% with the water jet at different pressures of 20 MPa, 40 MPa, 60 MPa, 80 MPa, respectively. The effect of rock breaking can be improved by increasing the pressure of water jet.

1. Introduction

With the increase in energy demand, the demand in coal production has also increased in the world. The coal accounted for 70% of the energy consumed in China, and the total demand for coal is increasing every year. The roadway excavation is the first step for coal mining, and the wear of cutting mechanism of roadheader is extremely serious in this process, which has a considerable impact on the reliability of the equipment. In order to solve this issue, the researchers indicated that the cutting force and wear of cutter can be reduced by the assistance of water jet as well as the dust produced in the cutting process (Lu et al., 2013; Yang et al., 2011). Therefore, the method of hard rock breaking with assistance of water jet is utilized to improve the life and efficiency of the conical cutter.

A lot of studies on rock breaking with assistance of water jet were conducted by the scholars and engineers. The outcome of the investigations and the conclusions drawn by various authors appear often controversial due to the great variability of the experimental conditions involving a large number of parameters (Handewith et al., 1985; Hood et al., 1992). The reduction in the average values of interaction forces variable from 65% to 80% were measured by Ropchan et al. (1980) and Dubugnon (1981), while experiments made by Fenn (1989) gave a reduction of 40%. Tomlin (1982) conducted his experiments on a roadheader mining machine at an underground test site, and discovered that water jets have a substantial health and safety benefit in that they cause the dust make at the cutter head to be reduced significantly. Fowell et al. (1992) pointed out that the major disadvantages of water jet are the sealing required between the tool and the cutting head and the cost of the jet nozzle built into the tool. The experimental research on the rock drilling with assistance of high pressure water jet was investigated by Veenhuizen (1997), the results showed that the drilling efficiency could be increased by 1.5–1.6 times with assistance of ultra-high pressure water jet. The excavating performance of PCD cutter with assistance of water jet was tested by Ciccu et al. (1999, 2004), Ciccu and Grosso (2010) the results indicated that with the assistance of water jet, the wear of cutter reduced, the excavating speed increased, and the excavating depth increased by more than 80%. Abrasive water jet is a kind of

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liquid–solid two-phase media jet formed with the mix of abrasive and high speed water, the high-speed particle beam formed by the abrasive can apply a high frequency impact to break the hard rock efficiently (Momber and Kovacevic, 1999; Momber, 2001). The mechanical analysis was studied for the hard rock breaking of PDC cutter with assistance of abrasive water jet, which showed that the cutting force reduced by 30–50%, and the reduction rate of cutting force was almost unaffected by the cutting depth, when the water jet was placed on the back of the PDC cutter (Lu et al., 2008).

With the development of computer technology, numerical simulation methods have been widely applied to the study of rock breaking process. Nowadays, scholars have taken a variety of numerical simulation methods to analyze the rock breaking mechanism. Su and Ali Akcin (2011) created the graded particle assemblies to predict numerically tool forces from cutting tests in PFC3D, and the micro-properties were calibrated by modeling the uniaxial compressive strength test. Carpinteri et al. (2004) carried numerical analysis for rock crack by Franc2D software. Rojek et al. (2011) simulated the rock breaking process by 2D and 3D discrete element model. The numerical analysis model of rock under the impact of ultra-high pressure water jet was established by Li et al. (2010) based on the fully-decoupled fluid–structure interaction theory, and the process of rock breaking with water jet was simulated according to the established fully-decoupled fluid–structure interaction model, the constitutive damage model and the failure criterion. The numerical simulations were carried out by Li et al. (2008) to study the propagation and attenuation of stress wave in the rock under the high pressure water jet with different impact speeds, which showed that the propagation velocity of stress wave was proportional to the impact velocity, and the greater the water jet velocity was, the sooner the attenuation of stress wave was. The rock breaking process of shield machine cutter was simulated by finite element method, and the effects of cutter geometry and cutting parameters on the cutting force were analyzed by Xia et al. (2011). The discrete element model for performance analysis of cutterhead excavation was established by Wu et al. (2013), the results indicated that the DEM model is a promising method replacing the field experiments to analyze the influences of the structural parameters on system performances, which are essential for structure optimization design of the cutterhead system of EPB machine.

The fruitful achievements of the above research provide a reference for this paper. However, the research on rock breaking with assistance of water jet were mainly conducted through various experiments, and the mechanisms of rock breaking are not unified due to the different experimental conditions, the complex interactions among rock, cutter and water jet, and the opaqueness of rock. In order to obtain the internal mechanical characteristics of rock and cutter and investigate the mechanisms of rock breaking, many numerical simulation methods have been widely applied, but little attention was paid on the arrangement of the cutter and the water jet. Based on this, the water jets placed on the front and rear of the cutter were researched to improve the efficiency of rock breaking. And the corresponding damage models were established based on the SPH and Lagrange algorithm to study the effects of water jets at different positions and pressures for the optimal parameters of rock breaking with assistance of water jet.

2. Model establishment

2.1. Mechanical model

Rock breaking with the assistance of water jet is a complex process that involves large, nonlinear and elastoplastic deformations. So, the water jet was dealt as smoothed particle hydrodynamics (SPH), and the Lagrange model was adopted to simulate the rock.

The interpolation theory is the key technology of the SPH algorithm, the partial differential equations under various boundary conditions are solved by a series of smooth particles, which are uniformly distributed (Ma et al., 2008a, 2008b; Wang et al., 2010). There is no grid connection among the particles which carry various physical quantities, and the transmission of the force among particles is based on the kernel estimation value. In hydrodynamics, the Navier-Stokes equation of fluid is acquired according to the SPH algorithm, shown as follows (Song et al., 2009; Monaghan and Rafiee, 2013):

$$\begin{cases} \frac{d\rho}{dt}(x_i) = \sum_{j=1}^{N} m_j(v(x_j) - v(x_i)) \cdot \nabla_i W_{ij} \\ \frac{dv}{dt}(x_i) = \left[\frac{\sigma^{\alpha\beta}(x_j)}{\rho_i^2} - \frac{\sigma^{\alpha\beta}(x_i)}{\rho_j^2}\right] W_{ij,\beta} \\ \frac{dE}{dt}(x_i) = -\sum_{j=1}^{N} m_j\big(v(x_j) - v(x_i)\big) \times \left[\frac{\sigma^{\alpha\beta}(x_i)}{\rho_i^2} + \frac{1}{2}\Pi_{ij}\right] \cdot W_{ij,\beta} + H_i \end{cases} \quad (1)$$

where $\rho(x_i)$ is the density of particle i, m_j is the mass of particle j, $\sigma^{\alpha\beta}$ is the stress tensor, $v(x_i)$ is the velocity of particle i, $E(x_i)$ is internal energy per unit mass of particle i, Π is artificial viscosity force, H is artificial heat flux, W is the kernel function.

The Lagrange algorithm is adopted to express the control equation of rock, as follows:

$$\begin{cases} \sigma_{ij,j} + \rho F_i = \rho \ddot{x}_i \\ \rho = J\rho_0 \\ N = S_{ij}\dot{\varepsilon}_{ij}V - (p+q)V \end{cases} \quad (2)$$

where x_i is the particle coordinate, $\ddot{x}_i$ is the acceleration, σ_{ij}, $\dot{\varepsilon}_{ij}$, S_{ij} are the Cauchy stress tensor, strain rate tensor and deviator stress tensor respectively, and $S_{ij} = \sigma_{ij} + (p+q)\delta_{ij}$. F_i is the body force of per unit mass, V, ρ, N are the volume, density and energy of the rock respectively, ρ_0 is the initial density, J is the change rate of volume, p and q are the viscous drag of pressure and volume respectively, and $p = -\sigma_{kk}/3 - q$.

2.2. Finite element models and boundary conditions

The SPH particles model of water jet was established as cylinder based on the practical condition, its diameter is 2 mm, and the target distance of water jet is 1 mm (Eghtesad et al., 2012). The theoretical value of the water jet victory v can be acquired according to the equation $v = 44.67\sqrt{p}$, p is the pressure of water jet. The cutter is conical, its length is 152 mm, the maximum diameter is 62 mm

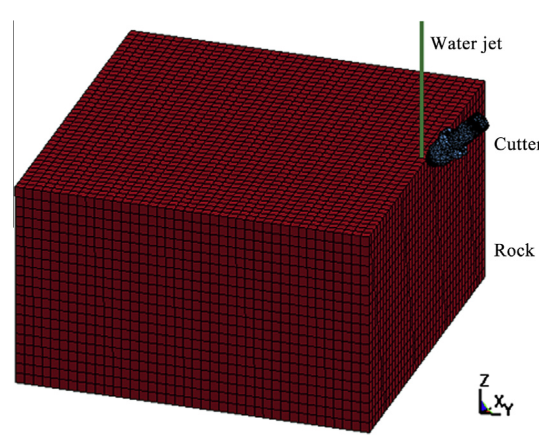

Fig. 1. Finite element model of rock breaking with assistance of water jet.