IOP Conf. Series: Materials Science and Engineering **324** (2018) 012032 doi:10.1088/1757-899X/324/1/012032

The research of breaking rock with liquid-solid two-phase jet flow

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Abstracts. Particle impact drilling is an efficient way of breaking rock, which is mainly used in deep drilling and ultra-deep drilling. The differential equation was established based on the theory of Hertz and Newton's second law, through the analysis of particle impact rock, the depth of particles into the rock was obtained. The mathematical model was established based on the effect of water impact crack. The research results show when water jet speed is more than 40 m/s, rock stability coefficient is more than 1.0, the rock fracture appear. Through the experimental research of particle impact drilling facilities, analysis of cuttings and the crack size which was analyzed through Scanning electron microscope consistent with the theoretical calculation, the validity of the model was verified.

1. Introduction

Particle impact drilling is not only rapid penetration of high efficient rock, but also greatly reduced drilling cost. At present, the research of particle impact drilling is still in the experimental stage, its theoretical system needs further improvement. Scholars have conducted a series of research on particle impact drilling. Liu Jialiang et al[1] analyzed the damage of rock by numerical analysis of high pressure water jet impact rock. Through the destruction of high pressure water jet rock, Ni Hongjian et al[2] concluded that the failure form of the rock was tensile failure, and showed a step type. Li Gensheng et al[3] scanned the broken rock of high pressure water jet by scanning electron microscope, and observed the broken form of rock. Li Qinglu et al[4] He calculated the depth of the rock and the stress of the broken rock by studying the incident velocity of the particle. Kuang Chunyu[5], Ren Jianhua[6], Zhao Jian[7] et al established the particle impact rock model by ANSYS/LS-DYNA finite element modeling software, and analyzed the mechanism of particle impact breaking rock. Lu Xiaocong et al[8] used Hopkinson pressure bar equipment to impact sandstone. Li Liyun et al[9] obtained the change rule of the release strain energy and the dissipated energy through the analysis of the deformation energy of rock structure. Li Xibing et al[10] studied the stress distribution diagram

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and the crack propagation law of rock under impact.

2. The effect of fluid-solid two-phase flow on rock

2.1. Mathematical modeling of single-particle impact rock

The motion equation and hertz equation are established for the impact of a single particle on the rock:

$$m_p z^{''} = -F^{'}(t) \tag{1}$$

$$F(t) = (\frac{z}{k})^{3/2} \tag{2}$$

where $k = \left(\frac{9}{64} \frac{1}{R_a} \left(\frac{1-\mu_1}{E_1} + \frac{1-\mu_2}{E_2} \right)^2 \right)^{1/3}$; k is the material characteristic parameter; R_a is the radius of curvature; z is the center of gravity of the particle; $F(t)$ is the impact force of the particle on the rock; μ_1 is the poisson ratio of the particle; μ_2 is the poisson ratio of rock; E_1 is the elastic modulus of the particle; E_2 is the elastic modulus of rock.The derivative of equation (2) is substituted into (1), When the motion equation of the particle satisfies $z=0$, $\frac{dz}{dt} = u_p$ So there is：

$$m_p u_p = -\frac{2}{5} k^{-3/2} z^{5/2} \tag{3}$$

where m_p is the mass of the particle, unit kg; u_p is the speed of the particle.

The maximum pressure depth $z_{\max}$ of the particle on the rock can be obtained:

$$z_{\max} = (\frac{5}{2} k^{3/2} m_p u_p)^{2/5} \tag{4}$$

The maximum impact of particles on the rock is:

$$F_{\max} = \frac{(\frac{5}{2} m_p u_p)^{3/2}}{k^{3/5}} \tag{5}$$

2.2 .The collision produces a crack

Using the formula of rock fracture mechanics, the crack length of rock is obtained:

$$K_1 = 1.12 \sigma_y \sqrt{\pi a_e} \tag{6}$$

The equation (5) is substituted into the formula (6) to obtain the length of the crack a_e:

$$a_e = \frac{1}{\pi} \left(\frac{k^{3/5} K_1}{1.12(\frac{5}{2} m_p u_p)^{3/2}} \right)^2 \tag{7}$$

where K_1 is the first kind of strength factor; σ_y is stress; a_e is the length of the crack.

3. Mathematical modeling

The strength factors of the first and second types of rock can be obtained

$$K_1 = 5.51 \overline{u} \sqrt{\pi a_0} + F(a) \sigma_{\max} \sqrt{\pi a_0} + 1.12 \sigma \sqrt{\pi a_0} \tag{8}$$

$$K_{\text{II}} = 1.12 \tau \sqrt{\pi a_0} \tag{9}$$

Where $\overline{u}$ is the average water pressure; K_1 is the first type of fracture strength factor; K_{II} is the second type of fracture strength factor; $a_0 = \frac{e}{\sin\beta}$; $\tau = F_1\cos\alpha$; $F(a) = 1.122 - 1.4R_e + 7.33R_e^2 - 13.08R_e^3 + 14R_e^4$; $\sigma_{\max} = \frac{6M}{H^2}$; $\sigma = \frac{N\sin\beta}{H}$; $R_e = \frac{e}{H}$; $H = e + h\bullet\sin\theta_L$.

The crack initiation angle θ_L can be calculated as follow:

$$K_1\sin\theta_L + K_{\text{II}}\left(3\cos\theta_L - 1\right) = 0 \tag{10}$$

The calculation method of crack fracture strength factor K_e can be expressed as follows:

$$K_e = \frac{1}{2}\cos\frac{\theta_L}{2}\left[K_1\left(1+\cos\theta_L\right) - 3K_{\text{II}}\sin\theta_L\right] \tag{11}$$

Therefore, based on the joint fracture strength factor and intact rock fracture toughness of the main control structure, the fracture mechanics expression of fracture rock stability coefficient is:

$$F_s = \frac{K_{\text{I}C}}{K_e} \tag{12}$$

where, the fracture toughness of the rock is $K_{\text{I}C}$.

In the process of operation, μ_L =0.5 and μ_V =0.8, fracture toughness of sandstone $\text{K}_{\text{I}C}$ =9.8 $MP\text{a}\bullet\text{M}^{1/2}$, $\beta = 85^\circ$ and so on. Figure 7 is calculated for equation (12). According to Regulation 9.5.5 of the Code for Landslide Prevention and Control Engineering, the stable state of the rock containing cracks can be determined according to the stability factor of table 1.

Table 1. The stability coefficient of rock F_s.

Fs	Fs＜1.0	1.0≤Fs＜1.3	1.3≤Fs＜1.5	Fs≥1.5
stable state	Unstable	Less stable	Basically stable	stable

According to the analysis of table 1, the stability of rock is unstable when the coefficient $F_S < 1.0$. The figure 1 shows that the stability of rock is unstable when the impact velocity of the particle is 40 m/s, the stability coefficient of the rock is 1. 0. When the particle velocity is greater than 40 m/s, the rock begins to fall off. When the velocity of the particle is less than 40 m/s, the stability coefficient of the rock increases exponentially, and the rock will not break and fall off.

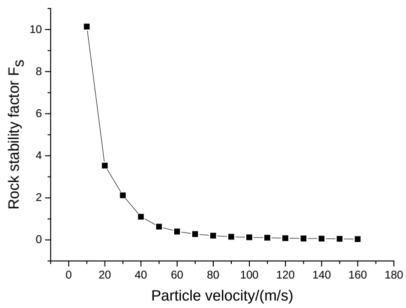

Figure 1. The velocity of particles and the stability coefficient of rock.

After each particle impact, the high pressure water acts on the rock, its crushing volume is:

$$V_w = h \bullet \left(\frac{H+e}{2}\right) \bullet \frac{\pi D}{n} \tag{13}$$

Since h is the depth at which particles invade the rock, substituting (4) into (13) yields:

$$V_w = \left(\frac{5}{2} k^{3/2} m_p u_p\right)^{2/5} \bullet \left(\frac{H+e}{2}\right) \bullet \frac{\pi D}{n} \tag{14}$$

where, D is the diameter of the particle.The volume relationship of rock with different particle velocities is shown in figure 2.

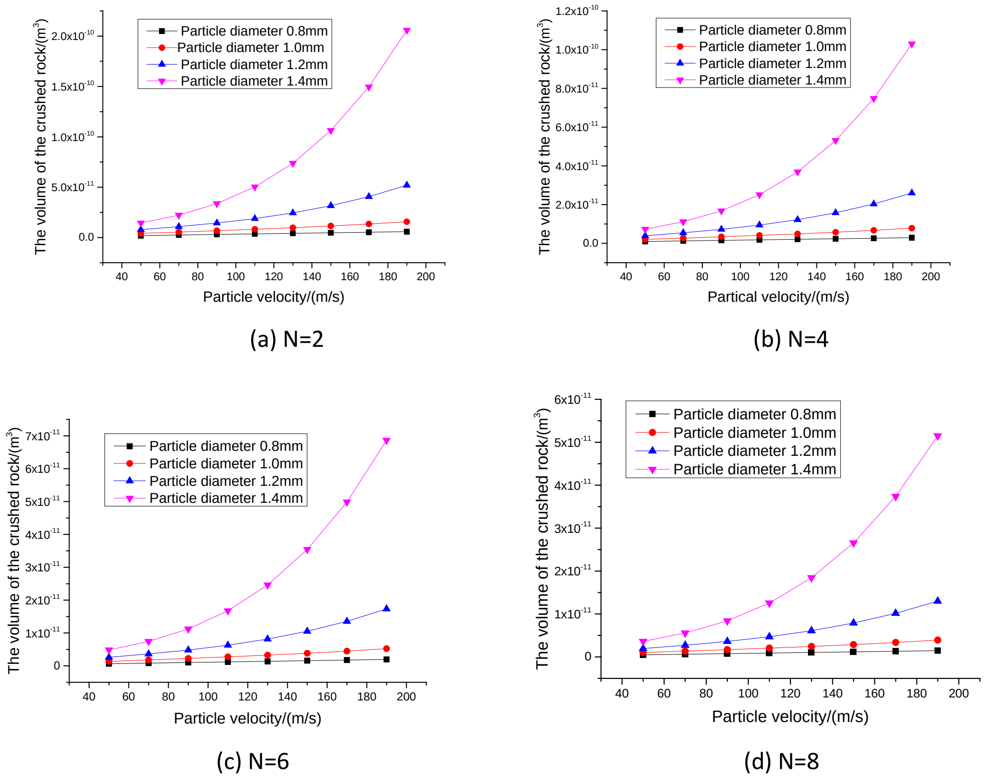

Figure 2. The volume of broken rock by water of different crack number.

It can be seen when the particle radius is more than 1 mm, the volume of water broken rock increases with the increase of particle velocity, and it increases linearly when the radius of the particle is less than 1 mm. The breaking volume of rock appears inflection point when the particle velocity is 150 m / s, the volume of broken rock is slow before the turning point, and the volume of broken rock increases rapidly after turning point.Through the above research, we can know that when the particle velocity is more than 150 m/s, the rock breaking effect reaches the best.

4. Experimental research

The diameter of the nozzle used is 4mm, the particle diameter is 0.8~1.4mm,the size of the granite is $250\text{mm} \times 250\text{mm} \times 100\text{mm}$ .In the experiment, the particles were added to the tank, and the volume of the particles in the high-pressure pipeline was controlled by adjusting the speed of the screw propeller. By adjusting the speed of high-pressure pump, control the speed of high pressure water in high-pressure pipeline, continuously for 30 seconds at different water speed, record the experimental data, observe the shape of rock debris, count the particle size distribution of the debris, and observe the rock fracture by scanning electron microscope. Table 2 is a set of parameters for the experiment.

Table 2. The distribution of the cuttings.

d<2mm	2mm<d<4mm	d>4mm
15%	60%	25%

During the experiment, the fragmentation of the rock is shown in figure 3, and the shape of the rock fracture pit is like an inverted funnel.

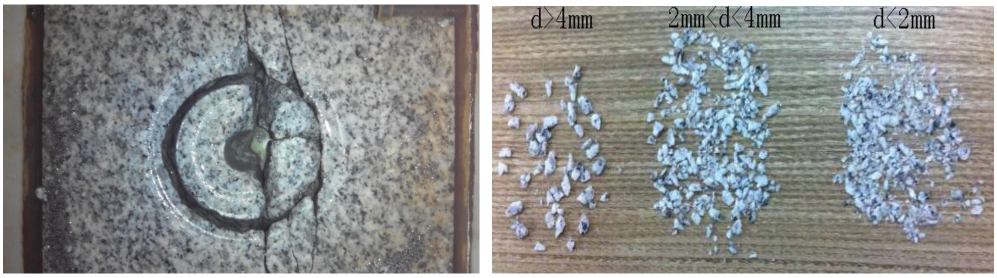

Figure 3. The picture of broken rock and cuttings.

5. Conclusions

By using the hertz theory to establish the mathematical model. When the impact velocity of water reaches 40 m / s, the stability coefficient is greater than 1.0, and the rock containing cracks begins to break.When the particle velocity reaches 150 m / s, the rock breaking effect is the best.Through the observation and study of rock debris in laboratory, the distribution proportion of cuttings diameter is obtained, and the volume is basically consistent with the theoretical analysis.

Acknowledgements

The authors would like to acknowledge financial support by the New Century Excellent Talent Training Fund of Heilongjiang Province in China, Project: 1254-NCET-005 and Postdoctoral Scientific Research Development Fund of Heilongjiang Province in China, Project: LBH-Q15018.

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