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Mathematical model of rock stress under abrasive slurry jet impact based on contact mechanics

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ABSTRACT

With development of water jet technology, abrasive water jet (AWJ) has become a new tool for cutting hard rock, which is widely used in stone processing, tunneling, and mining. Abrasive slurry jet (ASJ) is superior to AWJ in its ability and efficiency of rock cutting and breaking due to the addition of high-polymer. However, the stress field of rock impacted by ASJ directly affects the cutting and breaking efficiency, but there is no unified microscopic mechanism of rock failure under ASJ impact due to the uncertain contact type between the rock and the abrasive particles. In this paper, contact mechanics is used to establish a new mathematical model of rock stress under ASJ impact, which shows the rock stress distribution. Moreover, the mathematical model was solved numerically and presented in a rectangular coordinate system, from which the rock stress concentration area and failure type can be obtained. The results show that rock stress concentration appears at four areas (the center, edge, axis of particle indentation, and the edge of slurry jet), where rock is apt to be broken with axial compressive failure, radial tensile failure, shear failure, and radial tensile failure, respectively. Moreover, the rock stress caused by abrasive particle impact is much larger than that by slurry jet impact.

1. Introduction

As a new tool of rock cutting, abrasive water jet (AWJ) and abrasive slurry jet (ASJ) have been widely applied to various engineering works, such as stone processing, tunneling, and mining.[1–3] In terms of rock broken by water jet, researchers have done a lot of research works and obtained numerous academic achievements. The Johnson–Holmquist-Concrete nonlinear constitutive model was used to study the formation, propagation and attenuation of stress waves during rock breakage by pulsating jets, which showed that effect of pulsating jets on the stress wave is very strong.[4] An experiment was carried out to study the rock cutting depth of AWJ with the Taguchi experimental design method, which showed that the cut depths decreased with increasing traverse speed and decreasing abrasive size.[5] The evolution of rock damage impacted by high pressure water jet was simulated with nonlinear FEM and a dynamic rock damage model. The numerical results showed that most of rock damage and breakage takes place in several milliseconds, the main damage behavior under a general continual jet is tensile damage caused by the rock unloading and the jet impacting, and the evolvement of rock damage shows step changed.[6,7] The Arbitrary Lagrange Euler (ALE) fluid-solid coupling penalty function method was adopted to establish a model of rock breaking under AWJ with continuum damage mechanics and micro damage mechanics. The results showed that the body of rock damage and breakage is mainly attributed to impact and the internal process of breaking rock experienced three stages within 50 μs.[8]

Momber summarized the recent work on wear and erosion mechanics of rocks and cementitious composites and presented a definition of relevant wear types.[9] Dehkhoda studied the capacity of pulsed water jets on rock breakage and finally found that the pulse lengths and pulsation frequencies of the water jet were key parameters in generating the internal damage.[10] The processes of mechanical excavation assisted with water jet were studied, which showed that the contribution of jet is to weaken the rock and to increase the stress.[11] Lu developed a new kind of hard rock mechanical drilling technique with the abrasive water jet assistance, which can reduce the impacting force and the bit wear in the hard rock drilling.[12] Finite element method (FEM) and smoothed particle hydrodynamics (SPH) was used to simulate the rock fragmentation process by water jet and discussed the effects of impact velocity, confining pressure, and structure plane on rock dynamic fragmentation.[13] Mu used FEM and SPH method to investigate the mechanism and damage evolution of AWJ impaction on rock[14] The results showed that the penetration depths are in relation to the shape and density of abrasive and the damage gradient is inversely

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Fig. 1. Abrasive slurry with high-polymer.

proportional to the distance from surface impacted by AWJ.

According to the above literature review, most of the papers aim at the capacity of water jet in rock cutting, while there are few studies on the rock stress distribution, which is significant to reveal the mechanism of rock failure impacted by abrasive water jet. Therefore, this paper used the contact mechanics to establish a new mathematic model of rock stress under ASJ impacting, which was solved numerically to show the rock stress distribution intuitively. Moreover, the stress concentration and failure type of rock at different position was obtained. The paper provides a new idea to study the microscopic mechanism of rock failure under ASJ impacting.

2. Assumptions for rock stress mathematic model

It is the key problem to quantitatively study the stress field of rock impacted by ASJ that abrasive particles were dispersed in the jet randomly. As shown in Fig. 1, abrasive particles were evenly distributed in the slurry due to the addition of high-polymer, which is benefit for researching the rock stress field. However, certain assumptions are still needed to reach the quantitative mathematic model of rock stress under ASJ impact.

Hypothesis 1. Rock is the half infinite space, which has no initial cracks.

Hypothesis 2. ASJ is cylindrical, who hit the rocks surface vertically and has no divergence.

Hypothesis 3. Every abrasive particle is spherical and has the same velocity.

Hypothesis 4. Abrasive particles are layered, which are uniformly distributed in the slurry jet (Fig. 2).

Hypothesis 5. The impact force of slurry jet is uniformly distributed on the rock surface within the jet diameter.

3. Establishing process for rock stress mathematic model

3.1. Theoretical basis of contact mechanics

Fig. 3 shows the geometrical relationship between pressure domain and stress calculation point, which can be used to obtain the stress distribution. And it has been reached with the contact mechanics under uniform pressure or Hertz pressure.[15]

3.1.1. Stress formula of uniform pressure on the circular domain

For points inside the circle:

$$\overline{\sigma_r} = \overline{\sigma_\theta} = -\frac{1}{2}(1 + 2\nu_2)p \tag{1}$$

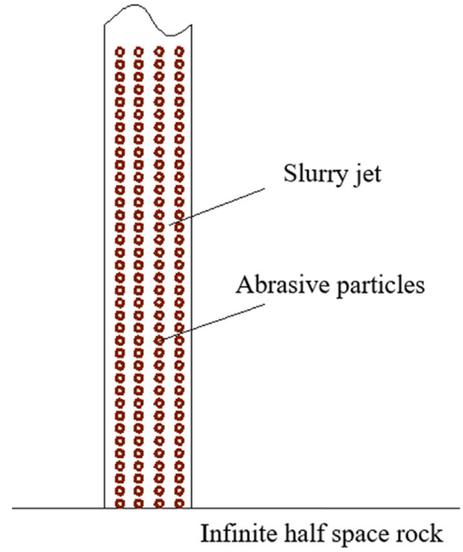

Fig. 2. Schematic diagram of rock impacted by ASJ.

$$\overline{\sigma_z} = -p \tag{2}$$

For points outside the circle:

$$\overline{\sigma_r} = \overline{\sigma_\theta} = \frac{(1 - 2\nu_2)(1 + \nu_2)pa^2}{2r^2} \tag{3}$$

$$\overline{\sigma_z} = 0 \tag{4}$$

For points on the circle axis:

$$\sigma_r = \sigma_\theta = -p\left[\frac{1 + 2\nu_2}{2} - \frac{2(1 + \nu_2)z}{(a^2 + z^2)^{1/2}} + \frac{z^3}{2(a + z)^{3/2}}\right] \tag{5}$$

$$\sigma_z = -p\{1 - z^3/[a^2 + z^2]^{3/2}\} \tag{6}$$

In the above formulas, $\overline{\sigma_r}$ is the radial stress, $\overline{\sigma_\theta}$ is the tangential stress, $\overline{\sigma_z}$ is the normal stress, p is the uniform pressure, ν_2 is Poisson ratio of the rock, a is radius of the circle, r is the distance between calculation point and circle center, and z is the distance between calculation point and rock surface.

3.1.2. Stress formula of Hertz pressure on the circular domain

Fig. 4 is the schematic diagram of rock impacted by abrasive particle under concentrated force, which belongs to the Hertz contact problem. According to the Hertz contact theory, pressure distribution, radius and depth of indentation can be calculated as follows:

$$p(r) = \frac{3P}{2\pi a^3}\sqrt{a^2 - r^2} \tag{7}$$

$$a = \sqrt[3]{\frac{3PR}{4}\left(\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2}\right)} \tag{8}$$

$$\delta = \frac{a^2}{R} = \sqrt[3]{\frac{9P^2}{16R}\left(\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2}\right)^2} \tag{9}$$

where $p(r)$ is the pressure distribution, P is the concentrated force, a is the indentation radius, δ is indentation depth, R is the abrasive particle radius, ν_1 is Poisson ratio of the particle, E_1 is the elastic modulus of particle, and E_2 is the elastic modulus of rock.

For points inside the indentation:

$$\overline{\sigma_r} = \frac{P(1 - 2\nu_2)}{2\pi a^2}(a^2/r^2)[1 - (1 - r^2/a^2)^{3/2}] - (1 - r^2/a^2)^{1/2} \tag{10}$$

$$\overline{\sigma_\theta} = -\frac{P(1 - 2\nu_2)}{2\pi a^2}(a^2/r^2)[1 - (1 - r^2/a^2)^{3/2}] - 2\nu(1 - r^2/a^2)^{1/2} \tag{11}$$