Powder Technology 320 (2017) 179–190

Contents lists available at ScienceDirect

Powder Technology

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

The propagation of stress waves in rock impacted by a pulsed water jet

Yongzhi Xue, Hu Si *, Qianting Hu

State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University, Chongqing 400044, China
School of Resource and Environmental Science, Chongqing University, Chongqing 400044, China

ARTICLE INFO

Article history:
Received 10 January 2017
Received in revised form 17 April 2017
Accepted 17 June 2017
Available online 30 June 2017

Keywords:
Pulsed water jet
Propagation
Stress wave
Smooth particle hydrodynamics

ABSTRACT

Pulsed water jets have been widely applied in the field of underground mining because of their unique advantages. Revealing the mechanical mechanism of rock breaking under a pulsed water jet is significant in advancing the application of pulsed water jets in the rock crushing process. Based on continuum mechanics and interpolation theory, this paper establishes a numerical model to simulate the propagation of stress waves in rock by adopting the method of smooth particle hydrodynamics (SPH). According to the simulation results, this paper presents a quantitative approach to schematize the propagation of stress waves in the time-space dimension. The waveforms of stress waves in the selected path and the effective stress history of test particles are obtained to quantitatively describe the propagation of stress waves. Relying on the approach, the effects of jet velocity and rock properties on the propagation of stress waves are investigated. The results show that in the rock model, the influence area, propagation speed and attenuation rate of the stress wave all increase with increasing jet velocity. Moreover, the mean effective stress of a test particle in the numerical model increases with increasing jet velocity. Of the rocks considered in this paper, granite shows the greatest mean effective stress acting on the test particle, propagation speed, and attenuation rate of the stress wave.

1. Introduction

Water jets have been used for rock erosion in mining operations for centuries. A low-pressure, high-volume jet is typically used to erode weak rocks, which are subsequently sluiced for mineral separation and further processing [1]. High-pressure, low-volume water jets have been seriously considered for cutting rock since the 1960s [2] and were first proposed for use in rock breaking using a conical pick in the 1980s [3]. Since these developments, many scholars have focused on the factors related to the cutting performance of water jets [4].

A pulsed water jet is a non-continuous jet composed of a series of discrete water slugs, which are normally teardrop shaped due to aerodynamic effects. Pulsed water jets typically generate cyclical impact forces as a sequence of short-duration pressure pulses on a target material. A considerable amount of evidence has shown that pulsed water jets can cause significantly greater damage than an equivalent continuous water jet [5–8]. This distinguishing feature results in a significant reduction in the cutting specific energy for pulsed water jets and also attracted increased research attention for this technique. In the early 1980s, Johnson et al. proposed the concept of a self-excited oscillation pulsed water jet and studied the effects of the nozzle structural parameters on its erosion performance [9]. Subsequently, several fundamental theories, e.g., impact action theory, water hammer theory, water wedge effect theory, cavitation theory and fatigue damaging effect theory, were established to describe the mechanism of rock breakage under a pulsed water jet [10–13]. These qualitative and semi-quantitative theories explained the phenomenological characteristics of rock superficially broken under a water jet. However, a uniform theory based on a more quantitative research approach is still needed.

The mechanical behavior of rock under the impacting process is complicated because it is associated with the hydro-mechanical coupling effect. Laboratory experiments, which are commonly used to analyze the fragmentation and damage pattern of rock samples after impact, cannot adequately determine the instantaneous stress state of the rock model and infer its mechanical mechanism. The development of computer technology made it possible to study the propagation of stress waves in rock using numerical approaches. The numerical method has been used to effectively simulate various complex physical processes and has developed into a mature tool in the field of geotechnical engineering. For example, Ni et al. [14] provided equations for the fluid, the rock and the rock damage model for the entire process of a water jet breaking rock. HH Bui et al. [15] simulated soil-water interactions based on the smoothed particle hydrodynamics (SPH) method. Liu et al. [16] simulated the impact of a high-pressure water jet on rock with a high confining pressure based on the arbitrary Lagrangian-Eulerian (ALE) algorithm. Junkara et al. [17] simplified the abrasive jet to a single abrasive particle and simulated the process of particles impacting the target material at different speeds and angles. They obtained the optimal incidence angle and the optimal incidence rate by comparing their numerical results with experimental data. Bai et al. [18] simulated

* Corresponding author at: School of Resource and Environmental Science, Chongqing University, Chongqing 400044, China.
E-mail address: sihu@cqu.edu.cn (H. Si).

http://dx.doi.org/10.1016/j.powtec.2017.06.047
0032-5910/© 2017 Published by Elsevier B.V.

the process of rock fragmentation under water jets at varying incident velocities based on the hydro-mechanical coupling method and a penalty function. These successful cases confirm the feasibility of using the numerical method for studying the propagation of stress waves in rock under a pulsed water jet.

This paper establishes a numerical model for rock impacted by a pulsed water jet based on the SPH method. Unlike traditional contributions that directly analyze the stress wave based on the stress nephograms, the new approach presented in this paper discusses the propagation of stress waves quantitatively. Using this approach, this study schematizes the propagation of stress waves in the time-space dimension. In addition, the waveforms of the stress waves in the selected path and the effective stress history of the test particles are clearly plotted, which provides a meaningful basis for describing a stress wave. In addition, the effects of jet velocity and rock properties on the propagation of stress waves are discussed.

2. Methodology

For a pulsed water jet composed of a series of discrete water slugs, the numerical model established in this paper focuses on the impact process of a single water slug. The condition of rock under the impact of a single water slug is shown in Fig. 1. The rock erosion that occurs as a result of the water jet is a typical nonlinear dynamic process that involves large deformation and a high strain rate. To simplify the calculation program, the model assumes the following: 1) the water jet is regarded as a continuous homogeneous fluid; 2) the rock is assumed to be continuous, uniform and isotropic; and 3) the cavitation effect of the pulsed water jet is neglected. To avoid computation failure caused by mesh distortion, the SPH method is used to establish the numerical model. Because of the symmetry of the mechanical model, a 1/4 model is built in LS-DYNA, and the symmetry plane is defined using the key word 'SPH_SYMMETRY_PLANE'. The numerical model is shown in Fig. 2.

2.1. Governing equations in the SPH framework

SPH is a mesh-free Lagrangian particle method that was originally invented to solve astrophysical problems in three-dimensional open space [19–20]. Unlike grid-based numerical methods, such as the finite element method (FEM) and the finite difference method (FDM), SPH uses a set of arbitrarily distributed particles to represent a system and to approximate the corresponding partial differential equations

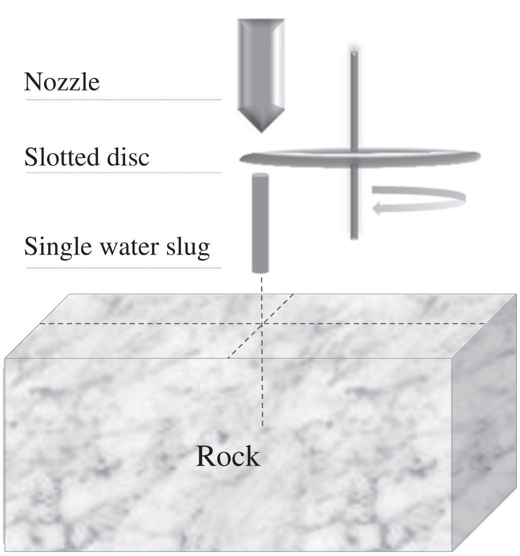

Fig. 1. The impacting condition of rock under a single water slug.

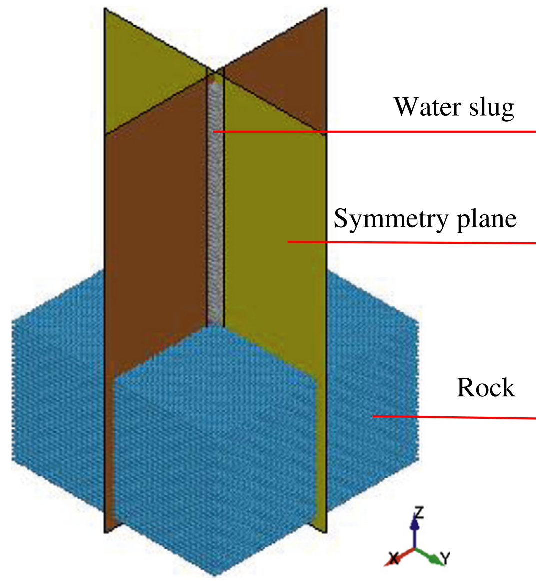

Fig. 2. The numerical model.

(PDEs). In SPH, a kernel function is used to approximate the field variables at any point in the domain [21–23]. The estimated value of a function $g(x)$ at location x is given in a continuous form by integrating the product of the function and the kernel function $W(x_i - x_j, h)$.

$$\{g(x)\} = \int_{\Omega} g(x_j) W(x_i - x_j, h) dx_j \tag{1}$$

where $\{g(x)\}$ is the kernel approximation, h is the smoothing length, and x_j is a new independent variable.

The value of the kernel function is zero everywhere except on a finite domain within the range of the smoothing length 2 h.

$$W(x_i - x_{j,h}) = 0 \text{ for } |x_i - x_j| > 2h \tag{2}$$

The kernel function is normalized as

$$\int W(x_i - x_j, h) dx_j = 1 \tag{3}$$

These requirements ensure that the kernel function is reducible to the Dirac delta function when h tends to 0.

$$\lim_{h\to 0} W(x_i - x_j, h) = \delta(x_i - x_j, h) \tag{4}$$

Therefore, the following is obtained:

$$\lim_{h\to 0} \{g(x)\} = g(x) \tag{5}$$

If the function $g(x)$ is known at only N discrete points, then the integral of Eq. (1) can be approximated by a summation:

$$\{g(x)\} = \int_{\Omega} g(x_j) W(x_i - x_j, h) dx_j \approx \sum_{j=1}^{N} \frac{m_j}{\rho_j} g(x_j) W(x_i - x_j, h) \tag{6}$$

where m_j and ρ_j are the mass and density of particle j, respectively, and m_j/ρ_j is the volume associated with particle j.

Eq. (6) constitutes the basis of the SPH method. The value of a variable at a particle is denoted by subscript i and is calculated by summing the contributions from a set of neighboring particles, which is denoted by subscript j, for which the kernel function is not zero.