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Mechanism and effect of jet parameters on particle waterjet rock breaking

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ABSTRACT

The particle (spherical steel particles) waterjet is a new type of waterjet that can effectively break rocks and other materials. In this study, the simulation combined with the experimental procedure was conducted for optimization of the jet parameters (such as velocity, water pressure, dwell time, concentration, diameter, and standoff distance) for the rock breaking performance modeling of a particle waterjet. In particular, the changes in rock and particle properties following impact were analyzed based on the Smoothed Particle Hydrodynamics (SPH) method by using the ANSYS-DYNA software. The rock breaking experiments were performed by altering the particle waterjet parameters, with consideration to field applications. Moreover, the effects of particle waterjet parameters on the impact depth and breaking volume were identified. The rock breaking efficiency factor was analyzed by investigating various jet parameters. Overall, the simulation results were in good agreement with the experimental results. The results demonstrated that the rebound effect constituted an important factor in the crater diameter determination. Both the impact depth and breaking volume efficiency factor decreased with the increase in the water inlet velocity. Owing to the effects of deeper craters on the actual impact velocities of the particles, the impact depth and breaking volume efficiency factor decreased as the dwell time increased. Owing to the interference caused by the collisions between the incident and rebound particles, both the impact depth and breaking volume efficiency factor decreased as the concentration increased. The impact depth increased rapidly when the dwell time was below a critical time (40 s). When the particle concentration exceeded a critical value (3%), both the impact depth and breaking volume increased slowly, thus significantly decreasing the rock breaking efficiency. For the appearance of a deeper and wider crater, the optimized standoff distance was ranged from 20 to 30 mm. This analysis provided a realistic approach for the optimization of the particle waterjet parameters in rock breaking.

1. Introduction

The particle waterjet is utilized in rock cutting [1,2] or in the shot blasting treatment technology [3,4] and is similar to the abrasive waterjet. However, spherical steel particles with a greater diameter (ranging from 0.5 to 5 mm) and lower particle concentration (ranging from 0.5 to 5% by volume) are utilized in the particle waterjet, which make it different from abrasive waterjet [5,6]. The steel particles act as an important factor in the erosion of rocks with a waterjet. The particles erupting from the nozzle at a high speed and frequency impact the rock within an extremely short time period and upon an extremely low sized contact area. The instantaneous contact stress is significantly high, thus changing the conventional rock breaking trend and significantly increasing the energy utilization [7,8].

The particle waterjet cutting performance is a nonlinear impact dynamics problem affected by various factors such as jet pressure, standoff distance, particle concentration, and the material. Moreover, the target material can be removed from the particle impact accelerated by water at a high velocity [9–11]. The solid particle erosion consists of the following two parts: deformation damage removal and cutting removal [12]. The rock is penetrated by particles with a high instantaneous dynamic load, high deformation, and short dwell time [13]. By the utilization of both the Newton motion equation and law of Meyer, the equation of the white iron crater volume penetration by particles was established, whereas the abrasive cut depth was proportional to the abrasive kinetic energy [14]. Experiments were also carried out for analyzing the effects of the cavity height on cavity erosion under a gas–solid flow. The spatial distribution of particles within the cavity

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and erosion related to particle impacts for the variable cavity aft wall heights and for two particle sizes (44 and 106 μm) were studied. The maximum erosion rate was quite significant for higher sized particles [15]. A comprehensive modeling and computational study was presented for the erosion in elbows determination due to sand particles being entrained in air both by simulation and experimental methods, indicating that as the velocity increased, the metal loss increased following a power law [16].

With the objective of identifying and revealing the practical applications of a particle waterjet, investigation of the effects of the waterjet parameters on rock breaking performance is extremely important and highly desirable. The cutting depth efficiency tends to increase with increasing water pressure and traverse speed and with decreasing standoff distance. The cutting volume efficiency is strongly dependent on the standoff distance [17]. According to literature, with the contribution of the abrasive water jet, the drilling depth increased by ~63%, the thrust force and torque were reduced by ~15 and 20%, respectively, whereas the bit wear reduced significantly [18]. Both the theoretical analysis and experimental measurements demonstrated that the volume of the crater created by individual particle impingement, with the impingement velocity having been ranged between 5 and 11 m/s, was linearly proportional to the particle kinetic energy [19]. The kinetic energy of the wear particles that were removed increased linearly along with the erosion depth [20]. As the extent of strains exceeded the elastic limit, the impacted solid particles skidded over the surface. The threshold strain was theoretically derived as a function of the impact velocity and the rotating velocities as well as the particle surface contact duration [21]. A phenomenological model of the three-phased flow inside an abrasive waterjet machining cutting head was presented. The model was validated by an extensive set of experimental data with wide variations in cutting-head geometry, operating pressure, and abrasive mass flow rates [22]. An analytical model considering the size and shape of the abrasive particles was developed for the prediction of the brittle polycrystalline material total cut depth [23]. The tensile fracture caused by the shock pressure wave of abrasion was the main reason for the breaking of the rock [24,25]. A framework for sand collision modeling was presented including the effects of elastic, elastic–plastic and plastic deformations, surface adhesion, and size dependent property variations of sand [26]. The effects of pressure confinement on rock damage were analyzed by the ANSYS implicit–explicit solution [27]. The rock breaking caused by particle impact was investigated by the one-dimensional stress wave theory [28]. The abrasive wear is a rapid and severe process due to the contact between the abrasives and the solid material surfaces. This type of wear is usually classified into the following two categories: (i) the 2-body abrasive wear and (ii) the 3-body abrasive wear [29]. An integral approach with consideration of both the plastic and elastic–plastic material removal modes was presented. The erosion was characterized by two failure modes, the intercrystalline fracture and lateral cracking, whereas the power exponent regarding the particle velocity effects was 2.44 [30,31].

The smoothed particle hydrodynamics (SPH) simulations were utilized for particle embedment simulation. Regarding a given particle size, the embedment increased along with the incident velocity, whereas a critical minimum velocity, below which embedment would not occur, was predicted [32]. An SPH simulation of a cone penetrometer test in soft, cohesive soil was implemented. The higher soil strengths could be reproduced in the simulation if an improved shear model including the non-negligible friction angle was provided [33]. The energy absorption behavior of empty and aluminum metal foam-filled tubes with various taper angles was evaluated by the Finite Element Method (FEM) coupled with SPH [34]. A coupled FEM/SPH modeling technique was investigated for the numerical simulation of the quasi-static axial crushing of polystyrene foam-filled aluminum thin-walled aluminum tubes [35]. An FE methodology was developed for tensile stresses in the coating surface under a single particle impact analysis simulating the particulate erosion conditions [36].

Besides, most previous studies focused on rock cutting with the pure waterjet or abrasive waterjet, and not the particle waterjet, being different in utilization of spherical steel particles with a higher diameter and lower particle concentration. In a typical abrasive waterjet, the shape of the abrasives is irregular, and a garnet or quartz is usually utilized as the abrasive with diameter ranging from 0.06 to 0.3 mm. These characteristics of the abrasives lead to the serious wearing of the parts (such as nozzles and pipes) of an abrasive waterjet. In contrast, during a particle waterjet, the equipment wears only slightly. In most previous studies, the effects of waterjet were not considered, and the FEM/SPH method was rarely utilized for the investigation of the particle waterjet rock breaking problems. This technology can significantly enhance the rock breaking efficiency owing to the higher kinetic energy of particles. In practice, a multi large spherical steel particle impact is required for the rapid cutting of the rock. Furthermore, in most previous studies only the theoretical calculation or the experimental method was utilized for the investigation of the rock breaking performance.

In this study, a numerical simulation and experimental method was utilized for the establishment of the relationship between the rock breaking performance and waterjet parameters for hard rocks, with consideration of the effects of waterjet based on the SPH method, conforming to practical operational conditions in an effort for providing an efficient design for practical application.

2. Finite element model

2.1. Smoothed particle hydrodynamics-finite element method

In the SPH method, the continuous fluid is dispersed to interact with particles, and the change in particles is utilized to describe the change in the continuous fluid by the Diffuse Element Method. The SPH method is widely utilized in the high deformation of penetration study [32–35]. In this study, the SPH coupled with the FEM was applied to investigate the relationship between the particle waterjet parameters and the rock breaking performance (depth and volume). Furthermore, both the SPH and FE methods were utilized for the particle jet and rock models establishment, respectively.

Both the particle and water were modeled by the SPH method, which was a pure Lagrange method and did not require a mesh based upon the interpolation theory. A series of uniformly distributed smoothed particles was utilized having a variety of physical properties for the partial differential equations solution under various conditions. The kernel estimated value $f(x)$ could be expressed by using Eq. (1) [36–39] as follows:

$$f(x) = \int_{\Omega} f\left(x'\right) W\left(x - x', h\right) dx' \tag{1}$$

where $f(x)$ is the function of the 3D coordinate vector x, Ω is the support domain of the point x, $x - x'$ is the distance between the particles, h is the smooth length of the SPH particle changing along with time and space, and $W(x - x', h)$ is the kernel function, usually defined by the auxiliary function $(\theta(x - x'))$:

$$W\left(x - x', h\right) = \frac{1}{h(x - x')^d} \theta\left(x - x'\right) \tag{2}$$

where d is the space dimensionality.

The cubic b spline curve is most commonly utilized for a smooth function in the SPH method as described by the following equation:

$$\theta(u) = C_b * \begin{cases} 1 - \frac{3}{2}u^2 + \frac{3}{4}u^3, |u| \le 1 \\ \frac{1}{4}(2 - u)^3, 1 \le u \le 2 \\ 0, |u| \ge 2 \end{cases} \tag{3}$$