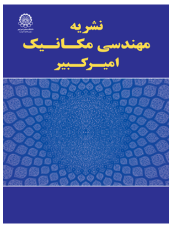

Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 55(8) (2023) 201-204
DOI: 10.22060/mej.2023.22439.7619

Numerical modeling of rock cutting with abrasive waterjet to determine the optimal parameters affecting cutting depth and volume

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ABSTRACT: In this research, the optimal parameters have been investigated with the aim of increasing the efficiency and improving the quality of rock cutting using an Abrasive Water Jet (AWJ) through the modeling of high-velocity two-phase flow (water and abrasive). The rock-cutting process by AWJ has been simulated using the combined finite element method-smoothed particle hydrodynamics in LS-DYNA software. For this purpose, the effect of parameters of jet velocity, dwell time, changes in volumetric concentration, and changes in the diameter of abrasive particles on the cutting depth and cutting volume of siltstone and shale rock specimens have been investigated. Numerical modeling results showed that with increasing velocity, the cutting depth and cutting volume increased. As the dwell time increases, the energy used by the AWJ to cut the rock increases, which would lead to an increase in the depth and volume of the cut. By increasing the volumetric concentration of abrasive particles up to 3%, the depth and volume of the cut increased with a gentle slope, and after that, no significant improvement was observed. Also, by increasing the diameter of the abrasive particles up to 1.25 mm for siltstone and 1 mm for shale, the depth and volume of the cut increased at first, and after that, they remained constant or decreased.

Review History:

Received: Jun. 03, 2023
Revised: Nov. 22, 2023
Accepted: Nov. 22, 2023
Available Online:Dec. 05, 2023

Keywords:

Abrasive waterjet
Rock cutting
Finite Element Method (FEM)
Smoothed Particle Hydrodynamics (SPH)

1- Introduction

Nowadays, owing to the widespread use of decorative stones, and the need for precision in their cutting, various methods are used for precise cutting of rocks, among which waterjet is more attractive due to its lower cost, easier usage and safer operations. One of the advantages of waterjet is making a smooth cut without creating residual and thermal stresses after machining. In a waterjet, a stream of water or a stream of water and abrasive particles exits from a nozzle at a high speed which can cut a solid object.

If the waterjet can operate without abrasive particles, it is called pure waterjet, which is suitable for cutting soft materials such as wood, rubber, and paper. On the other hand, an Abrasive Water Jet (AWJ) is used to cut hard materials such as metal, rock, and concrete. Garnet (natural abrasive) is used in 80% of industrial applications [1].

In the AWJ, abrasive particles are injected into the water flow, and by the momentum transfer between the abrasive particles and the high-speed water flow in the nozzle, a two-phase flow (water and abrasive) or a three-phase flow (water, abrasive and air) is ready to cut a solid sample. One of the AWJs is the particle water jet whose mechanism is similar to AWJ with the difference that instead of numerous fine abrasive particles, coarse particles (0.5 to 5 mm) with a low concentration (1 to 5%) are used [2].

In this research, numerical modeling has been used to determine the optimal parameters for rock cutting with AWJ. For this purpose, according to the physical and mechanical properties of the rock, material 145 in the LS-DYNA software has been selected to model two samples of siltstone and shale. The results of this research may be helpful in improving rock cutting with waterjet and reducing the waste caused by the cutting process to a significant extent.

2- Methodology

In this research, the SPH-FEM numerical method is used to simulate the rock cutting by AWJ. In this way, abrasive particles and water are modeled by the SPH method, and rock is modeled by the FEM method.

The rock geometry is designed with 150 mm length, 75 mm width, and 75 mm height. The column of water and abrasive particles is created as a semi-cylindrical with a diameter of 4 mm and a length of 200 mm, which leads to an increase in the number of particles and an increase in the duration of the software execution, which results in more aureate modeling [3]; since the modeled column is not run out during the process of numerical modeling (Figure 1).

In our modeling, the effect of air in the combination of particles, as well as the effect of air on the rock, has been ignored, due to its insignificant kinetic energy in the cutting

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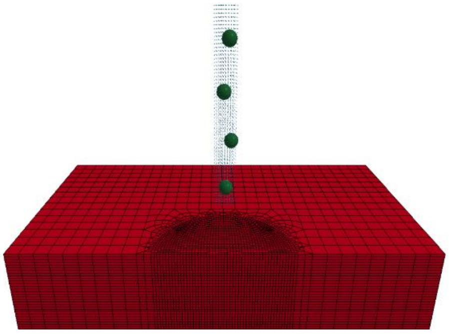

Fig. 1. SPH particle modeling of water and abrasive

Table 1. Geomechanical characteristics of rock samples

Rock	$\rho(\frac{kg}{m^3})$	$E\,(GPa)$	$UCS\,(MPa)$	ν
Siltstone	2730	3.3	44.4	0.26
Shale	2900	16.5	85	0.15

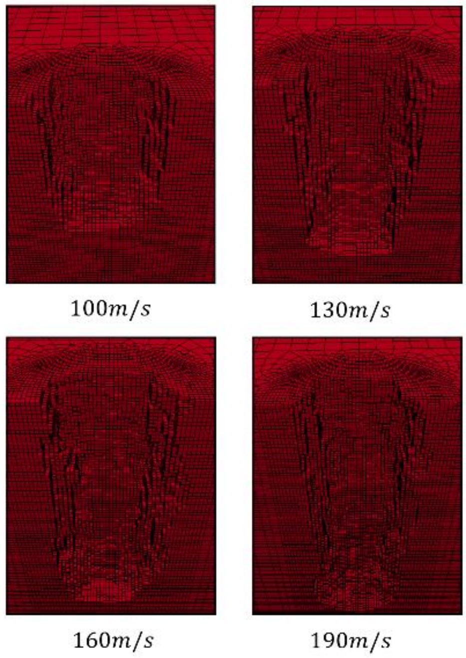

Fig. 2. Cutting geometry at different velocities

process [2]. Material 145 is selected from the software library as a suitable material for the finite element component of rock, which was proposed by Schwer and Murray [4, 5] and is called the Schwer-Murray Cap or Continuous Surface Cap. This model can properly describe many important mechanical behaviors of rock, concrete, and soil [6]. To determine the parameters of Material 145, the geomechanical characteristics of the rock including density, uniaxial compressive strength, Poisson's ratio, and Young's modulus should be determined. These characteristics are determined for 20 samples of siltstone and shale in the Rock Mechanics Laboratory of Bu-Ali Sina University, and the average results are summarized in Table 1.

For water, the material MAT_NULL and the Gruneisen equation of state have been selected from the software library [7]. Also, spherical steel particles have been used to model the abrasive particles by the MAT_ELASTIC material in the software, assuming that the steel particles are not deformable.

The command Contact_Eroding_Nodes_To_Surface in LS-DYNA software is used to define the contact between abrasive particles and rock. When water and abrasive particles hit the rock, the velocity of the particles gradually decreases. To simulate this phenomenon, the Initial_Velocity_Generation command has been used to apply the initial velocity to SPH particles of water and abrasive.

3- Results and Discussion

According to the results, by increasing the jet velocity, the kinetic energy of particles grows, and this makes the rocks to break faster. Moreover, as the dwell time increases, the depth and volume of the cut may also increase by a low rate at first, and then they increase quickly. Figure 2 shows the cutting geometry at different velocities for siltstone. At velocity of 100 m/s, the shape of the cut is not favorable. By rising the velocity to 190 m/s, the depth and volume of the cut gradually increase, and the shape of the cut approaches a cone. The results of the effect of velocity on the cutting depth and volume for both rocks are respectively shown in Figure 3.

In general, by increasing the concentration of abrasive particles, the depth and volume of the cut will increase with a gentle slope, and the concentration of 3% can be considered an optimal value. The results of the effect of changing the abrasive diameter on the cutting depth and volume of both rocks for a constant concentration of 1% show that by increasing the diameter of the abrasive particles up to a certain value (1.25 mm for siltstone and 1 mm for shale), the depth and volume of the cut increase at first, and after that the trends will decrease.

4- Conclusions

In this research, due to the extensive capabilities of waterjets in cutting decorative stones, the SPH-FEM numerical modeling has been used to investigate the effect of parameters affecting the quality of cutting depth and volume in two samples of siltstone and shale. The results are summarized as follows: (I) As the velocity of the water jet increases, the kinetic energy of the two-phase jet increases, and the depth and volume of the cut will increase. (II) The longer the dwell time on rock samples, the depth and volume of the cut will increase. (III) By increasing the volumetric

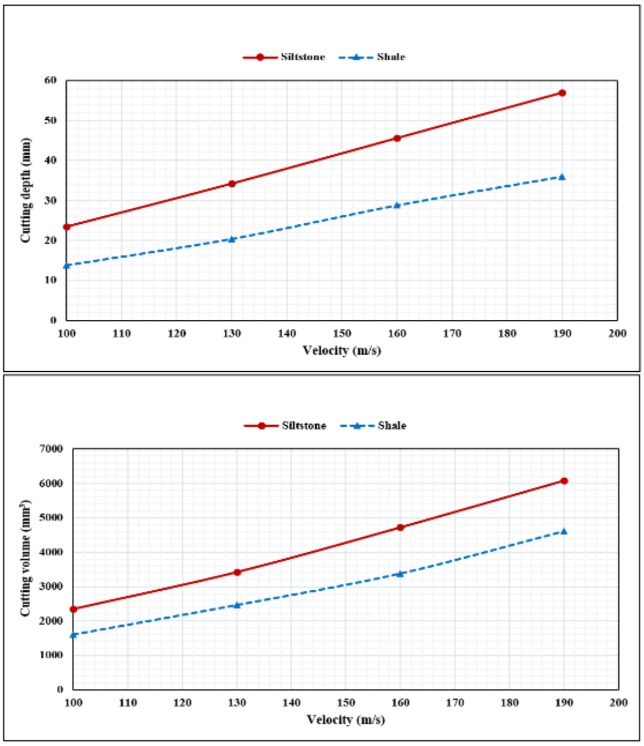

Fig. 3. Effect of jet velocity on the cutting depth and cutting volume

concentration of abrasive particles up to a specified value of 3%, the depth and volume of the cut increased with a slight slope, and after that, no significant improvement was observed. (IV) The effect of increasing the mass of abrasive particles up to a certain value with a smaller particles prevails over the increase in the number of particles with a lower mass. This specific diameter is about 1.25 mm for siltstone and about 1 mm for shale.

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HOW TO CITE THIS ARTICLE

S. Mahdevari, P. Bakhtiari HaftLang, H. Sayehvand, Numerical modeling of rock cutting with abrasive waterjet to determine the optimal parameters affecting cutting depth and volume, Amirkabir J. Mech Eng., 55(8) (2023) 201-204.

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