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Numerical investigation of rock removal performance based on abrasive size effect in abrasive waterjet drilling using a DEM-FEM coupled approach

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ABSTRACT: This study numerically explores the effect of abrasive particle size on rock removal performance in abrasive waterjet (AWJ) drilling using a DEM-FEM coupled modeling approach. The target rock was represented using the RHT constitutive model to simulate brittle failure under repeated high-energy impacts, whereas the garnet abrasives were modeled using the discrete element method (DEM) to capture their motion and interactions with the rock. Rock removal was evaluated in terms of eroded internal energy, which reflects the energy required to remove the material. Results show that larger abrasive particles, despite making fewer contacts, transfer higher kinetic energy with each impact, resulting in more effective drilling. Conversely, smaller particles produce lower drilling efficiency with more uniform and stable contact forces. These findings suggest that the energy delivered per particle is more critical to drilling performance than the number of impacts, offering valuable insight for selecting optimal abrasive conditions in future AWJ field operations.

KEYWORDS: Abrasive waterjet drilling, rock removal performance, abrasive particle size

1 INTRODUCTION

Urban overpopulation has increasingly reduced the availability of usable area on the surface. As a result, underground space development has become an inevitable trend and is actively being implemented worldwide. Abrasive waterjet (AWJ) technology is an excavation method applied in various industries (Momber & Kovacevic). This technology utilizes high-pressure water and abrasive particles and it ensures precision by accurately removing the target material. To date, it has been widely adopted in the geotechnical field due to its advantages of low noise, minimal vibration and reduced dust reduction as well (Oh & Cho, 2013). Thus, these benefits lead AWJ technology to be recognized as a sustainable solution in geotechnical engineering. AWJ drilling is a specialized application of AWJ technology. It is capable of penetrating target materials regardless of their type, and it can also expand pre-existing drill hole by creating additional fractures (Lu et al., 2013). Due to these advantages, AWJ drilling can be considered as a key excavation method. Therefore, understanding the influence of various parameters on AWJ drilling performance, as well as the mechanisms by which a high-speed waterjet accelerates abrasives, is essential for maximizing its effectiveness.

1.1 *Mechanisms of AWJ technology*

The intensifier pump generates high-pressure water within pump system. After the accumulator restores the water, it flows from pump system to waterjet system through a narrow pipe. As it passes through a small-diameter orifice, the water is transformed into a high-speed jet. This jet accelerates the injected abrasives in the mixing chamber. The accelerated abrasives, aligned by the focusing tube, continuously strike the target material with high energy. A cross-section of the waterjet system is shown in Figure 1.

1.2 *Effective parameters in abrasive waterjet drilling*

Various factors, such as waterjet system parameters, abrasive characteristics, target material properties affect the drilling performance. Waterjet system parameters include intensifier pump pressure, stand-off distance (SOD), jet exposure time, geometry of focusing tube. In abrasive characteristics parameters, abrasive particle size, abrasive flow rate (AFR), abrasive hardness play significant role in drilling efficiency. The target material, considered to be granite in this study, is characterized by parameters such as uniaxial compressive strength and rock hardness.

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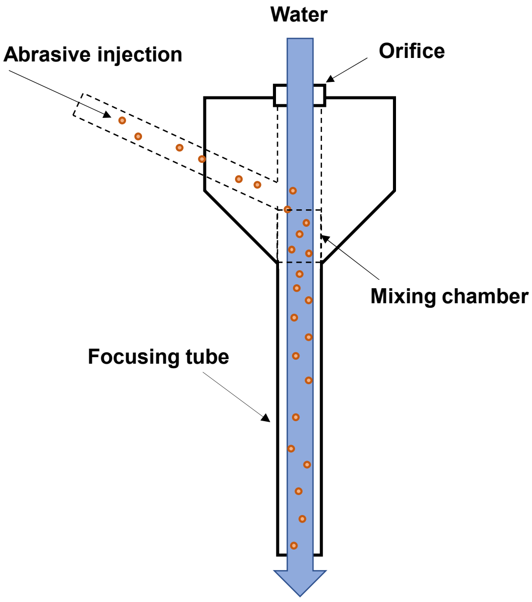

Figure 1. Cross-section of the waterjet system.

1.3 *Objective of this study*

Among these various factors, according to the previous research, effect of abrasive size has a significantly influence on the geometry of drilling hole (Hwang et al., 2025). It implies that the drilling performance is highly dependent on the variation of abrasive size effect. Therefore, in this study, numerical approach was utilized to deeply understand the effect of garnet size on rock removal performance. ANSYS LS-DYNA, a commercial software was used to simulate AWJ granite drilling.

2 NUMERICAL ANALYSIS METHODOLOGY

DEM-FEM coupling approach for simulating abrasive waterjet drilling process was adopted as the numerical modeling. since the continuous impact of accelerated abrasive mainly affects the rock drilling, the effect of water was considered negligible.

2.1 *DEM for abrasive particle*

Discrete element method (DEM) in ANSYS LS-DYNA can be utilized to track the position, velocity and acceleration of each granular abrasive particles based on Newton's equations of motion (Flores-Johnson et al., 2016).

$$m_i \frac{d^2 x_i}{dt^2} = \sum_j c_{ij} + m_i g I_i \frac{d^2 \emptyset_i}{dt^2} = \sum_j M_{ij} \qquad (1)$$

Where m_i is mass of abrasive particle i, c_{ij} denotes the interaction force between particle i and j, M_{ij} indicates moment from particle j to i (Zhou et al., 2025). To consider the interaction between discrete elements, CONTROL_DISCRETE_ELEMENT keyword parameters in previous research were selected to simulate the garnet abrasive particles as non-spherical and wet (Du et al., 2020). The garnet abrasive was modeled by MAT_ELASTIC keyword, which is valid for describing the elastic behavior ofs solid. Several parameters are shown as Table 1.

Table 1. Material parameters of abrasive

Parameter	Symbol	Value	Unit
Young's modulus	E	68	GPa
Mass density	ρ	3790	kg/m^3
Poisson's ratio	v	0.3	

2.2 *FEM for granite*

Lagrangian grid-based finite element method (FEM) has been widely adopted to solve solid mechanics problems (Feng et al., 2012). To model the granite subjected to high-frequency impact, MAT_RHT keyword was utilized. Riedel-Hiermaier-Thoma (RHT) constitutive model was developed for brittle materials such as concrete and rock. Since this model includes three limit surfaces (inelastic yield surface, failure surface, and residual surface), strain hardening, strain-rate effects, and pressure dependency, numerous researchers have modeled granite using RHT model. In this study, most of the parameters of RHT model referenced Li's model (Li et al., 2025), except mechanical properties such as compressive strength, elastic shear modulus and relative tensile strength.

Table 2. Mechanical parameters of granite

Parameter	Value	Unit
Mass density	2700	kg/m^3
Compression strength	238	MPa
Tensile strength	10	MPa
Elastic shear modulus	33.579	GPa
Poisson's ratio	0.3	-

2.3 *Contact algorithm of DEM-FEM coupled approach*

In erosion modeling, it is advantageous to implement CONTACT_ERODING_NODE_TO_SURFACE contact type, since it updates eroding surfaces as the particles delete target structure. Penalty-based contact method were used to avoid penetration issues and to compute contact force between the spherical particles and structures. Contact force is calculated by multiplying contact stiffness coefficient by the allowed penetration length.

2.4 *Modeling setup*

2.4.1 *Model geometry and mesh*

The FEM-simulated target rock had dimensions of 10 ×10×12mm. To discretize the given domain, a fine mesh of 0.1mm hexahedral elements was applied. The total number of the elements was 600,000.

2.4.2 *Boundary conditions*

BOUNDARY_NON_REFLECTING keyword by setting the side surfaces of the rock was used to eliminate the size effect of the granite. BOUNDARY_SPC_SET keyword is for constraining bottom of the granite.

2.4.3 *Injection conditions for DEM*

DEFINE_DE_INJECTION_ELLIPSE keyword was employed to model the injection of DEM particles into the target rock. In this keyword, the center of the injection plane, the length of the circular injection plane along X-axis and Y-axis in the coordinate system(CID), and initial velocity of injected particles can be specified. In this study, injection area and initial injection velocity were referenced from Hwang's work (Hwang et al., 2025). Due to the computational cost, activation region for abrasive (DEM) was constrained by defining an DEFINE_ACTVIE_REGION keyword. Gravitational load was defined by using a LOAD_GRAVITY_PART keyword. The model configuration is shown as in Figure 2.

2.4.4 *Numerical analysis cases*

To identify the effect of abrasive size on rock removal performance, the following parametric study cases were designed. The termination of the analysis was set as 500μs.

Table 3. Numerical analysis cases

Parameter	Value	
Intensifier pump pressure [MPa]	*320*	
Abrasive flow rate [g/s]	*5*	
Stand-off distance [mm]	*50*	*100*
Abrasive particle size [mm]	*0.07*	*0.07*
	0.18	*0.18*
	0.25	*0.25*

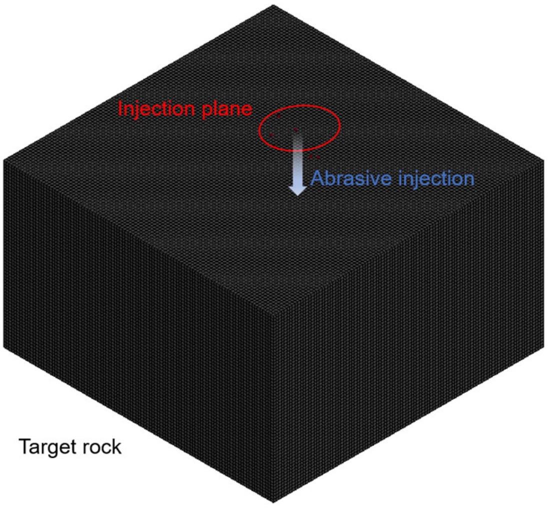

Figure 2. Injection plane and abrasive particle injection configuration

3 RESULTS AND DISCUSSION

3.1 *Effect of abrasive size on rock removal performance*

Rock erosion was induced by accelerated abrasives, as shown in Figure 3. After eroding the target rock, the rock removal performance was evaluated by eroded internal energy, which indicates the energy associated with deleted elements. The increase in the eroded internal energy of the target rock indicates that a greater amount of energy is required for element removal. Therefore, a higher eroded internal energy can be interpreted as improved rock removal performance. As shown in figure 4 and 5, the impact of larger abrasive particles makes a significant contribution to enhancing the drilling performance, although the number of abrasive particles decreases as particle size increases at the same abrasive flow rate.

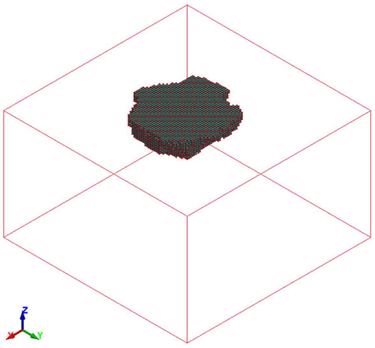

Figure 3. Rock erosion due to accelerated abrasive particles

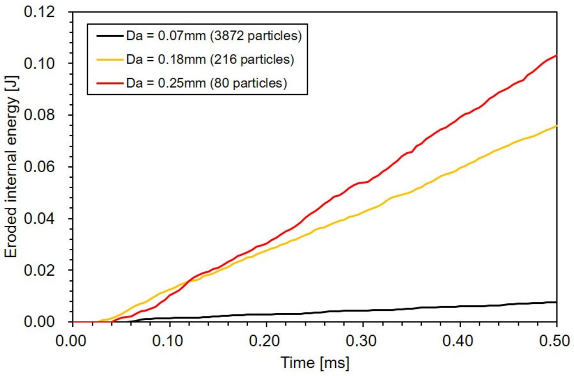

Figure 4. Time-dependent variation of the eroded internal energy of the target rock according to the diameter of abrasive particle (Stand-off distance : 50mm)

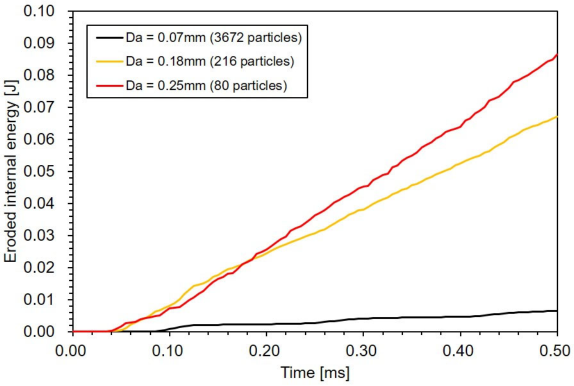

Figure 5. Time-dependent variation of the eroded internal energy of the target rock according to the diameter of abrasive particle (Stand-off distance : 100mm)

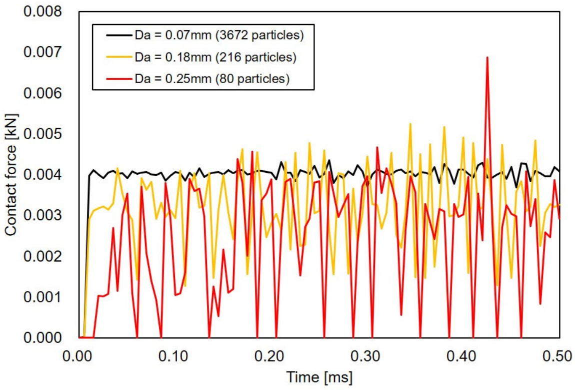

Figure 6. Time-dependent variation of the contact force between target rock and abrasives (Stand-off distance : 50mm)

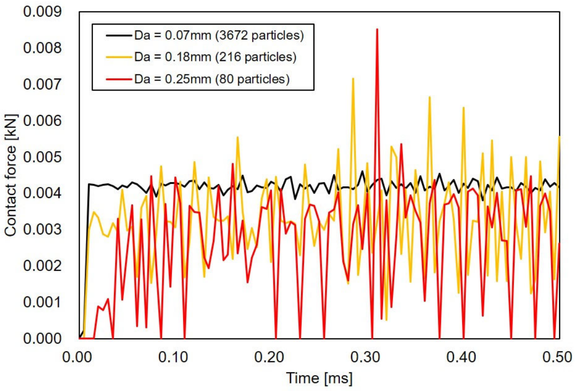

Figure 7. Time-dependent variation of the contact force between target rock and abrasives (Stand-off distance : 100mm)

Figure 6 and 7 shows the contact force occurred between DEM abrasive particles and FEM target rock. With smaller abrasive particles, a greater number of abrasives interacted with the rock, resulting in a relatively consistent contact force, whereas larger particles contacted the rock in significantly fewer numbers but produced a greater rock drilling effect. This suggests that the greater kinetic energy transferred by larger particles plays a more dominant role in enhancing rock removal efficiency rather than more frequent and uniform contact.

4 CONCLUSIONS

This study investigates the effects of abrasive particle size on rock removal performance in abrasive waterjet (AWJ) drilling of granite, using a DEM-FEM coupled numerical approach. The target rock was modeled using the RHT constitutive model to capture the brittle failure behavior under high-frequency abrasive impacts, while garnet particles were simulated using the discrete element method to account for individual particle motion and particle–rock interactions. The simulations were performed for different abrasive sizes at constant abrasive flow rate and two stand-off distances. The main findings of this study can be summarized as follows

- The DEM–FEM coupled approach effectively simulated the AWJ drilling process, enabling detailed evaluation of abrasive particle–rock interactions and erosion.

- Larger abrasive particles, despite fewer particle–rock contacts at the same abrasive flow rate, generated higher eroded internal energy due to greater kinetic energy of each abrasives, resulting in improved rock removal performance.
- Smaller abrasive particles produced more frequent and uniform contacts with relatively consistent contact forces, but their lower individual impact energy led to reduced drilling efficiency.

This study provides a foundational basis for optimizing abrasive parameters in future field applications of abrasive waterjet technology.

5 ACKNOWLEDGEMENTS

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