Numerical investigation of rock breaking mechanisms by high pressure water jet

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Abstract

Many factors and complexities are involved in breaking rock with a high-pressure water jet, which has made it difficult to explain the rock breaking internal mechanisms. This in turn has constrained the applications and development of water jet technology. In this work, we use numerical simulations to analyze the influence of jet incidence angle, jet velocity, nozzle diameter, number of jets, transverse velocity, and rock physical properties on the rock breaking efficiency. This has important practical implications for future research on rock breaking with high pressure water jet, as well as for the applications of water jet technology. For example, we established that there are two threshold pressures in the process of water jet rock breaking in our model. When the jet pressure becomes greater than the first threshold pressure, the rock breaking mechanism is erosion mainly through water wedging, and when the jet pressure exceeds the second threshold, the rock breaking mechanism is hammer punch dominated by water hammer effect.

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1. Introduction

At present, the internal mechanism of a high pressure water jet and the associated physical process have not been explained exactly. Therefore, the theoretical research of breaking rock by a high pressure water jet lags behind its practical applications [1]. Moreover, the significance of this approach for breaking rock in deep and ultra-deep drilling has been increasing [2].

In this work we utilize a nonlinear dynamic finite element method to simulate the process of striking and crushing rock using a high pressure water jet. Furthermore, we focus on the effect of several factors on the rock breaking efficiency, including jet incident angle, jet velocity, nozzle diameter, jet numbers, traverse velocity and rock physical properties. These factors have important practical implications for the development and application of...
approaches using a high pressure water jet, as well as for the improvement of the associated basic theory.

2. Numerical simulation

We first simulate the high pressure water jet and the rock structural properties, after which we use a dynamic contact method to analyse the stress changes in the rock [3]. The jet and rocks are then considered as two objects touching each other, so that the assumptions about the stress state of the docking surfaces can be ignored when the high pressure water jet strikes the rock at a constant speed. This makes it possible for the simulated model to be closer to the actual process of a jet striking the rock. A semi-wireless large unit is attached to the sides and the bottom of the model, in order to simulate a wireless remote state outside the model, as well as that various mechanical parameters are 0. In this 3D model we use a plane of symmetry contacting the rock as a rigid contact body. It is also assumed that there is no coupling with a friction force at the point of contact with the plane of symmetry and the rock also cannot be separated from the plane of symmetry.

Jet materials are considered as perfectly plastic in the analysis, and the yield stress is set to 0. The rock used in the simulation is sandstone, with its mechanical parameters set according to Table 1:

| Classification | Compressive strength (MPa) | Tensile strength (MPa) | Young’s modulus (MPa) | Poisson ratio | Density $\rho$ (kg/m$^3$) | Internal friction angle | Cohesion (MPa) |
|----------------|---------------------------|------------------------|-----------------------|--------------|--------------------------|------------------------|---------------|
| Sandstone      | 73.5                      | 9.3                    | $3.3 \times 10^6$     | 0.2          | $2.4 \times 10^3$        | 45$^\circ$             | 2.6           |
| Slurry         | 0                         | 0.5                    | $1.05 \times 10^3$    | 0.5          | 1.05$ \times 10^3$       |                        |               |

3. Results and discussion

3.1 Effect of the jet incidence angle on the rock breaking efficiency

The jet incidence angle is defined as the angle between the direction of the jet axis and the direction of the normal vector to the rock surface. The internal stress distribution of the rock varies depending on the angle, at which the water jet crushes the rock. This explains the great importance of the angle of jet incidence on the rock breaking efficiency [4]. Figure 1 shows simulation results demonstrating the dependence of the depth of rock breaking on the jet incidence angle. We can see that the depth of rock breaking first rapidly declines between angles of 0 (vertical incidence) and about 200, after which it increases again and reaches an optimal range around 360-420. This is somewhat different from the theoretical angle of 30$^\circ$, due to the fact that the rock breaking efficiency is also affected by other factors, such as internal friction angle and hydraulic friction coefficient.

![Fig. 1. Relationship between depth of rock breaking and jet incidence angle.](image)

3.2 Effect of jet velocity on rock breaking efficiency

Jet velocity is one of the most critical parameters determining the rock breaking efficiency [5]. There are two critical points in the curve relating the size of the rock breaking cross section and the speed of water jet, which is
shown in Figure 2. The first point marks the beginning of rock breakage, which occurs when the velocity of the water jet reaches 98 m/s. The second critical point is at 320 m/s, when the increase of the rock breaking area with increasing velocity rapidly accelerates. From this we can conclude that there exist two critical pressures, characterizing two different breaking mechanisms. When the jet pressure exceeds the first threshold pressure, the manifested rock breaking mechanism represents erosion, where the breaking is dominating by water wedging [6]. When the jet pressure becomes greater than the second threshold pressure, the rock breaking mechanism is hammer punch, mainly represented by a water hammer effect.

3.3 Effect of nozzle diameter on rock breaking efficiency

In terms of energy, the larger the diameter of the nozzle, the higher the energy with which the jet strikes, under certain circumstances determined by other physical quantities [7]. Figure 3 shows a linear relationship between the depth of rock breaking and the nozzle diameter.

3.4 Effect of the number of jets on rock breaking efficiency

Research on ultra-high pressure jet drilling has shown that a higher breaking efficiency is achieved with more than one jet, generally using arrangements of 2 to 3 nozzles of different diameters on the drilling bits. Here we report on our simulations of the process of rock breaking, when using two water jets at the same time. The two water jets enhance each other and achieve increased breaking depth and breaking area. Table 2 shows that the double water jet breaks an area that is 2.15 times larger than that broken by a single water jet. The increase in the breakage depth is 1.3 times.
Table 2. Comparison of breakage results when using a single and double water jet flows.

| Number of jets | Breaking depth/(mm) | Broken area/(mm²) |
|---------------|---------------------|-------------------|
| 1             | 5.8                 | 32.8              |
| 2             | 7.3                 | 70.7              |

3.5 Effect of transverse velocity on rock breaking efficiency

The main effect on the relationship between the crushed rock volume and the transverse velocity is imposed by the relationship between the water jet time and the jet crushing volume. After the water jet pressure exceeds the first critical velocity (see text in Section 3.2 above and Fig. 2), moving slowly of transverse velocity is along with the long-time jet impact and the larger broken depth. Moreover, the initial crushing of the rock by the water jet is completed within a few milliseconds. After that the crushing pit becomes deeper, the increase continues, but is slower than before, and when the action time is long enough, the depth of breakage basically becomes fixed. Figure 4 shows the relationship between the depth of breakage and the jet transverse speed. The volume of broken rock is defined as the product of the cross-sectional area of the breakage groove and the velocity of the jet. With the jet speed increasing, the energy consumption per unit volume of crushed rock decreases rapidly; therefore there exists an optimal jet speed.

![Fig. 4](image)

3.6 Effect of the physical properties of the rock on the breaking efficiency

Rock breakage by water jet can be classified as tensile or shear failure. Since the rock shear resistance and tensile capacity can be determined by its compressive strength, the analysis of the impact of the compressive strength has is related to the effect of the physical properties of the rock on the rock breaking efficiency. [8]. Figure 5 shows the numerical simulation of the relationship between the rock compressive strength and the breakage depth resulting from the application of a high pressure water jet. This figure shows that the greater the compressive strength of the rock, the smaller the crushing depth. The volume of crushed rock depends similarly on the rock compressive strength.
4. Conclusions

In this paper we analysed the factors influencing the rock breaking efficiency by high pressure water jet. For this purpose, we used numerical simulations, the results of which are in agreement with experimental observations. In addition, we demonstrated that the nonlinear dynamic finite element method used, coupled with a dynamic rock damage model, can be successfully applied to describe the process and mechanism of rock breaking by water jet. Furthermore, we showed that there exist two threshold pressures in the process of water jet rock breaking in this model. When the jet pressure exceeds the first critical pressure, the rock breaking mechanism is erosion, where rock breakage occurs mainly by water wedging. When the jet pressure becomes greater than the second threshold pressure, the rock breaking mechanism is hammer punch, dominated by a water hammer effect.

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