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# Experimental study of flow field structure of interrupted pulsed water jet and breakage of hard rock

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ABSTRACT

Interrupted pulsed water jet has great potential for application in hard rock breakage as it can be easily generated and controlled. The sharp nature of the head and tail of the jet significantly influences on water hammer pressure of the jet and efficiency of hard rock breakage. In this paper, the evolution of a single pulse was captured using high-speed photography and analyzed by numerical simulation. It was found that the velocity of the jet head was slower than the jet velocity at the nozzle exit, but the former still had high turbulent kinetic energy. A U-shaped structure was formed after the jet head made contact with the target, and it in turn affects the peak and duration of the water hammer pressure, as well as its distribution on target. The effect of stress wave propagation on rock breakage during erosion of granite by interrupted pulsed water jet was investigated by ultrasonic testing. Results showed that there were two modes of rock breakage, namely macroscopic fracture of rock blocks, and fixed-depth erosion hole formation. These were caused by the combined effects of the impact stress wave and the pulsating water wedge pressure. The effects of jet diameter, pulsation frequency and jet power on erosion rate and specific erosion energy were analyzed.



## 1. Introduction

Water jets have been used for rock breakage for centuries. Low-pressure and high-volume jets are used as an efficient means for breakage of soft rock. However, due to environmental considerations and the increasing industry demand of hard rock breakage, until today this approach is rarely used. Since 1960, rock breakage technology using high-pressure, low-volume jet gained popularity in scientific research and industrial applications[1]; and in particular, pulsed water jet provided a new research direction for hard rock breakage.[2,3] Pulsed water jet is a high-speed jet consisting of a series of discrete high-intensity short-duration water hammers with transient pressure pulses. The pressure of the water hammer responsible for erosion of the targets is composed of water hammer pressure and stagnation pressure, and it has been identified as a major factor driving rock breakage.[4,5] The pulsed water jet can be applied in several forms, such as compressed, interrupted and excited.[6] Of these, the interrupted pulsed water jet device controls the diameter, frequency and interval length of pulsed jet by adjusting jet pressure, rotational speed of the rotary disc, and the sizes of the nozzle, rotary disc and disc slots. It can generate completely interrupted pulses, which may eliminate the water cushion effect and fully utilise the water hammer pressure in rock breakage. In addition, it is simple to produce with good controllability for field applications.[7]

The erosion efficiency of the interrupted pulsed water jet is affected by many hydraulic factors, which include jet velocity, jet diameter, pulse length, pulsation frequency and power.[8] A large number of experimental studies have been conducted in an attempt to improve the erosion efficiency of the jet. For example, experiments conducted by Leach et al.[9] found that when the convergence angle was 13°, the straight nozzle had the best jet convergent form, and hence the highest rock-breaking effect. Brook and Summers[10] conducted the first experiments to interrupt the water jet using a slotted disc or by rotating the targets, and they found that the erosion depth and speed were significantly higher than those of the continuous jet. In their experiment, sandstone erosion depth and the average erosion rate were about four times those of the continuous jet at 41 MPa working pressure and a fixed target distance. To investigate the influence of

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pulsation frequency on jet erosion depth, Erdmann-Jesnitzer et al.[11] conducted experiments using interrupted pulsed water jet at different frequencies, and found that the average erosion depth was the highest at 100 Hz. Vijay et al.[7] performed experimental and theoretical studies on the erosion potential of interrupted pulsed water jet on hard rock. The flow loss caused by jet deflection during interruption was considered for the first time, and a flow coefficient of the interrupted pulsed water jet was measured in the experiment. The relationship between specific kinetic energy and pulsation frequency was also analyzed. Research of interrupted pulsed water jet has often focused on the effect of jet characteristics on erosion depth and prediction of deflection of jet flow. The process of formation and the structural features of interrupted pulsed water jet have only been scarcely reported in the literature. The sharp head and tail of the jet are associated with the level and duration of the water pressure, and hence is an important factor in terms of the erosion efficiency. This paper provides a theoretical approach on jet structures and related key parameters of the interrupted pulsed water jet. The formation of the jet is studied using high-speed photography and Computational Fluid Dynamics (CFD) simulation. The effect of parameters such as jet frequency, pulse length, jet diameter and power of the interrupted pulsed water jet on rock damage were analyzed using ultrasonic inspection techniques. Furthermore, crack formation and propagation and the destabilization conditions of the rock were also studied from the perspectives of the energy theory and fracture mechanisms, thereby providing a theoretical basis for industrial applications of interrupted pulsed water jet.

## 2. Experimental analysis of flow field structure of interrupted pulsed water jet

The testing system is shown in Fig. 1, which depicts the generating system for the interrupted pulsed water jet, high-speed camera, pressure sensors and the rotational speed control valve. The system pressure was 80 MPa, and the nozzle diameter was 3.429 mm. The rotational speed of the slotted disc was controlled at 780 rpm by the throttle valve of the hydraulic system. The power of the slotted disc was provided by the hydraulic motor, and the rotational speed was monitored in real time using a digital oscilloscope and a speed sensor. The German HiSpec2G high-speed camera was used and the shooting speed was set to 7437 fps. Each pulse generated by the rotation of two slotted discs was designed to have a very similar non-axisymmetric structure. The direction of the high-speed camera lens was set to be perpendicular to the jet direction, and the view angle of the camera was aligned to the jet axis and midpoint of the view. Each high-speed image had a width of 55 mm and a length of 250 mm. The initial shooting position was at a distance of 12 mm from the impact spot, so the capture range of the images was between 12 and 262 mm from the impact spot.

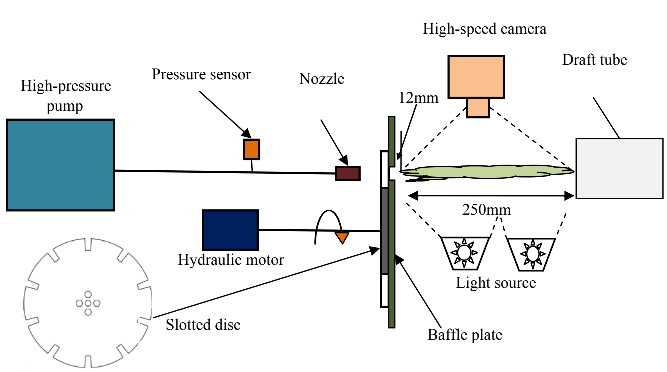


**Fig. 1.** Test system of interrupted pulsed water jet.

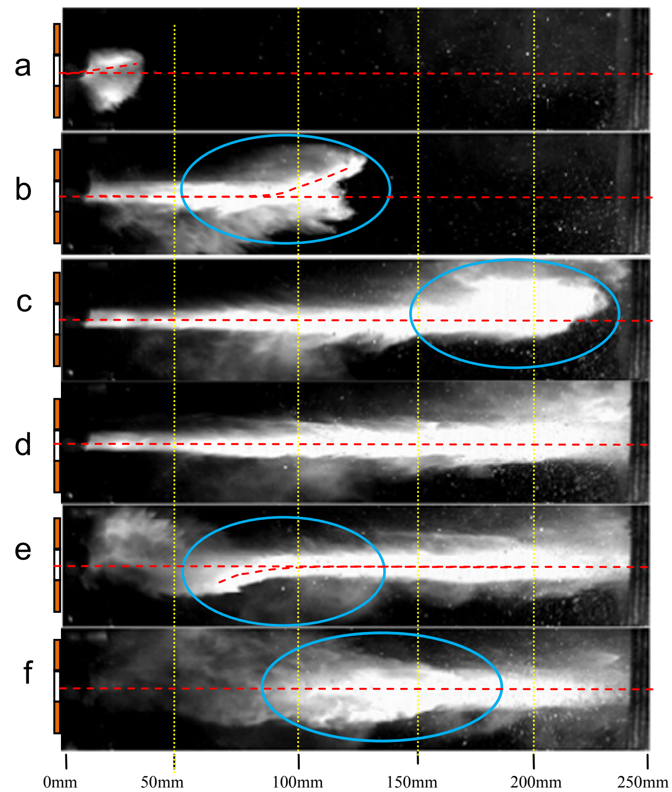


**Fig. 2.** Development of a single pulse of interrupted pulsed water jet.

Fig. 2 shows the process of structural change of a single pulsed jet at a time interval of 268.9 μs. At the beginning of jet formation, the jet head started to appear and the jet deflection angle was approximately 15° (frame a). After 268.9 μs, the head structure was completely formed and the jet deflection angle increased to about 25° (frame b). Afterwards, the axial velocity of the jet head was reduced by the interference of disc slots and a radial velocity of the jet opposite to the direction of movement of the disc slots was developed to deflect the jet head to one side (frame c). At the end of a single pulse, the tail was formed at a deflection angle of 15° and the deflection direction was the same as the direction of movement of the disc slots (frame e). Finally, due to the effects of Rayleigh instability of the shear layer (Rayleigh instability is that a vertically falling column of non-viscous liquid with a circular cross-section should break up into drops if its wavelength exceeded its circumference) and surface tension, the tail gradually detached from the main jet (frame f).

## 3. Numerical simulation of interrupted pulsed jet

Computer models with the same geometric size and the movement process of the jet generation device was created. The studied areas consisted of air section, disc slot section and air section with axial length of each section 9, 10 and 81 mm, respectively. The axial length from the nozzle to the target plate was 100 mm. The moving states of the three computational regions were the air space section and the air section were in relatively fixed states, while the disc slot section slided between the two fixed sections. Nozzle diameter, slot size and position were set referring to the jet structure experiment. A stationary target was set at 100 mm standoff distance for the study of the erosion pressure of the interrupted high-pressure pulsed water jet. Nozzle