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The internal failure of rock samples subjected to pulsed water jet impacts

Sevda Dehkhoda*, Michael Hood

CRC Mining, The University of Queensland, Brisbane, Australia

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ABSTRACT

The capacity of pulsed water jets for creating internal breakdown within a rock target was the subject of this investigation. The resultant, internal damage is defined as an increase in micro-crack density within the rock samples. It is attributed to the occurrence of a fatigue phenomenon resulting from the periodic impacts of high-velocity water-pulses and from the interaction of the induced stress-waves within the target material. This paper reports an investigation into the extent to which fatigue damage occurred in rocks that were subjected to pulsed, water jet impacts. For this purpose, the wave-attenuation capacity of rock samples, before and after being subjected to a pulsed water jet, was measured and the relative disparity between these two figures was then utilised as a measure of the potency of the pulsed water jets in producing an internal breakdown within the rock targets. The results indicated and confirmed the occurrence of internal damage in tested marble and granite samples. The pulse lengths and the pulsation frequencies of the water jets were found to cooperate in developing the internal damage and, depending on the rock type, one played a more significant role than the other.

1. Introduction

A pulsed water jet is a non-continuous, high-velocity jet composed of a series of discrete, water slugs. These slugs, when impacting a target, apply high intensity, short duration, transient stress pulses with a peak amplitude known as the water hammer pressure, followed by low-intensity, long-duration, stationary stress at a lower, stagnation pressure. While the magnitude and duration of the water hammer and of the stagnation pressures are dependent on the size and quality of the water pulses, the frequency of loading cycles is controlled by the pulsation frequency of the jet.

The application of pulsed water jets to rock cutting and rock fragmentation has been of interest for decades [1–7]; few of these studies have in practice, however, led to the widespread use of this technology. This has been partly attributed to the limited understanding of the rock-breakage mechanism of such devices. Effective rock breakage by a pulsed water jet depends on the impact stresses that are imposed by individual water pulses. These stresses are controlled by shape, size, and velocity of water-pulses. More importantly, rock breakage is influenced by the water pulse length and by the separation distance between the sequential pulses. An understanding of the individual and interactive effect of the pulse length and pulsation frequency on the failure process of a rock target is a prerequisite to the design of an efficient, pulsed, water jet apparatus.

Studies have shown that the direct interaction of the high-velocity water-pulses with rock target- material results in surface and subsurface damage [8–13]. Whether or not the stress waves, which are generated from cyclical impacts of high-velocity water-pulses, are capable of introducing internal, microstructural damage within treated, rock samples and the extent to which this type of damage occurs, have not yet been investigated.

A previous paper by these authors had studied the surface and subsurface damage in the top section of rock-targets, which had been impacted with pulsed water jets (part A in Fig. 1), and had identified the role and influence of pulse length and pulsation frequency on the quality and quantity of local failure [11]. This paper now examines the bottom section of the same pulsed, water jet, treated specimen (part B in Fig. 1) to measure and to determine the potency of pulsed water jets in producing internal breakdown within rock targets. There is a direct relationship between the internal imperfections of materials and their intrinsic, wave-attenuation properties [14,15]; an increase in the wave-attenuation capacities of the rock samples due to the impact of pulsed water jets has thus been utilised to quantify the amount of induced, internal, microstructural failure within treated rock-targets.

2. The pulsed water jet experiments

Pulsed, water jet, treatment experiments were conducted using an external-flow-interrupted, pulsed, water jet device (Fig. 2), where the high-speed rotation of a slotted disc in front of the

* Corresponding author. Tel.: +61 449 174 195.
E-mail address: sevda.dehkhoda@uqconnect.edu.au (S. Dehkhoda).

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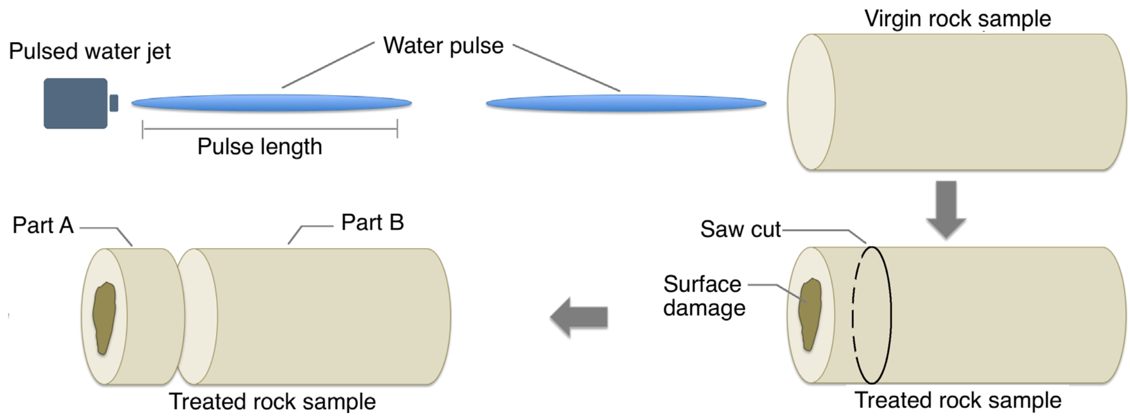

Fig. 1. A schematic view of the pulsed, water-jet experiments; part A of the treated specimen was used for surface and subsurface study [11]; part B is the subject of the current paper.

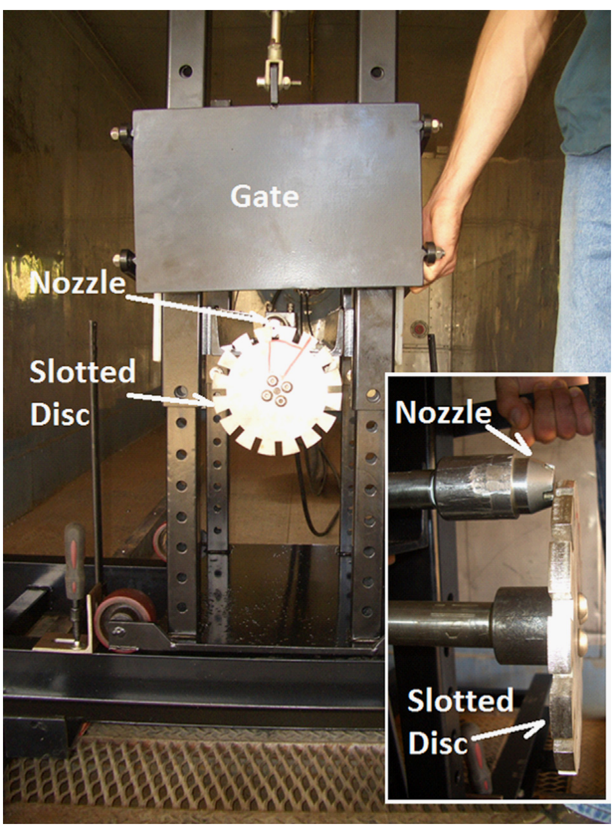

Fig. 2. The interrupted and pulsed, water jet [11,15].

continuous water jet was used to generate discrete water-slugs. Experiments were performed on core-shaped granite and marble samples (of a 55 mm diameter and with a height to diameter ratio of 2.4) with diverse mechanical and physical properties (Table 1). The rock specimens were placed within a Hoek cell and were confined at 6 MPa whilst being impacted by the pulsed water jets. The pulse lengths and pulsation frequencies were changed between experiments using slotted discs with different numbers of slots and slot lengths. Once the rock samples had been treated by a pulsed water jet under the conditions outlined in Table 2, the top, damaged sections were cut off and the remaining bottom sections were used to investigate the internal microstructural failure. The details of the pulsed water jet, the testing equipment, and the procedures and the parameters were described in the previous paper [11].

Table 1
The physical and mechanical properties of the rock samples (the test was based upon the ISRM standard)

Parameters	Granite	Marble
Bulk density (kg/m^3)	2640	2700
UCS (*MPa*)	210	78
BTS (*MPa*)	11.69	6.24
Secant Young Modulus (*MPa*)	60.93	68.53
Poisson's ratio	0.25	0.26
Fracture toughness ($MPa.\ M^{0.5}$)	2.22	1.91
Longitudinal wave velocity (*m/s*)	5257	5616
Shear wave velocity (*m/s*)	3046	3165
Dynamic Young modulus (*GPa*)	61	69
Dynamic bulk modulus (*GPa*)	73	85
Dynamic shear modulus (*GPa*)	24	27
Dynamic Poisson ratio	0.25	0.27
Shear quality factor	18	14
Acoustic impedance (*MPa s/m*)	13.88	15.16

Virgin (intact) and treated rock-samples were tested to determine the shear-wave, attenuation coefficients (Sections 2.1 and 2.2). The influence of the pulse length and pulsation frequencies on the amount of internal breakdown within the rock target was then investigated by comparing the calculated, shear-quality factors of the corresponding, virgin and treated samples (Section 3).

2.1. The methodology for measuring attenuation

When an acoustic wave travels within a medium, it attenuates for several reasons. Geometric spreading reduces the energy per unit area according to the inverse of the square of the distance from the source ($E/A \sim 1/r^2$). Since the amplitude of the acoustic wave is proportional to the square root of the energy ($\mathrm{Amp} \sim E^{1/2}$), pulse amplitude decreases with the distance from the source ($\sim 1/r$). In addition to this loss, wave energy, in an imperfectly elastic medium such as rock, diminishes as a function of time, or alternatively, length due to conversion to heat or viscous relaxation in the imperfections. The attenuation coefficient is proportional to the wave frequency whilst the amplitude of the wave is influenced by geometric spreading, reflections, scatterings and intrinsic damping [16].

In general, for a plane wave propagating in a medium, the amplitude of the stress or energy is written as:

$$A(x,t) = Ge^{\alpha(f)x}e^{i(kx-\omega t)} \quad (1)$$