Experimental and Numerical Study of Rock breakage by 
Pulsed Water Jets

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Abstract

Rock breakage is, arguably, the most important step in the mining process. Poor blasting practice produces large boulders that are difficult and expensive to handle. The presence of oversized boulders in draw-points can stop production in underground caving mines. Blasting and heavy impact hammers are the main techniques used in mines to fracture oversized rocks, but both impose undesirable extra costs as a secondary rock-breakage operation. Blasting is time-consuming and can damage the infrastructure, whilst impact hammers are cumbersome and cannot be used where boulders are not readily accessible. It is important, therefore, to develop more effective secondary rock-breakage techniques.

Preliminary research demonstrated that pulsed water jets are routinely able to break large (approximately 1m$^3$) boulders of competent hard rocks in less than a minute. Therefore, they can potentially be a more effective method for secondary rock-breakage. They can deliver high power intensity with a low reaction force meaning that a lightweight, flexible apparatus can be employed. The breakage mechanism of rocks under the impact of water pulses is, however, not yet clear.

A pulsed water jet consists of a series of discrete, large water drops travelling at high velocity. These apply cyclical impact forces of short duration onto the target material. The water impacts generate stress waves inside the rock samples and these waves can, potentially, influence the rock-breakage process. The contribution of the stagnation water pressure on the target after impact may also play a crucial role in fracture initiation and propagation in the rock. The geometrical properties of the jet are controlled and influenced by the method that is used to generate the water pulses. The original contribution of this research is the determination of the processes of water pulse formation and the discovery of key factors that influence rock fracture initiation and propagation.

A straightforward method was employed to generate a single water pulse using a hammer that stroke a piston, rested on top of a water-filled chamber. This impacting action pressurised the water, causing it to be expelled at high velocity through a nozzle that was mounted on the chamber axis opposite the piston. A theoretical investigation was undertaken to improve the understanding of this system for generating water pulses. A computational model, on the basis of continuity and momentum equations for a compressible viscous flow, was developed to simulate the pressure dynamics in the chamber. This model was used to optimise the relative sizes of the hammer, the piston, and the height of the water column in order to produce the largest and the highest-velocity water pulses. The model was validated experimentally using a purpose-built apparatus.
Research was conducted to measure the impact loading of the water pulses on a target material. The main challenge was to measure this load for an event that lasted for less than one microsecond. This obviously required an extremely fast-response sensing system to capture the induced stress wave from the water hammer pressure before it reduced to the stagnation pressure. Customised sensing and data acquisition equipment was developed for these measurements. PVDF (Polyvinylidene fluoride) shock gauges were selected as the most appropriate sensors because of their unique rapid response, large stress range, and large signal to noise ratio. PVDF polymer films are piezoelectric material and generate electrical charge in response to applied stress. A current-mode measurement method was chosen because of the high-speed nature of the phenomenon of interest. The derivative of the stress was measured and the signal was then integrated numerically. This measurement, in conjunction with the high-speed photography of the water pulses, was applied to a study of the coherence of the generated water pulses.

In the final stage of the research, experiments were conducted to examine the damage caused to confined rock specimens by sequences of water pulses of various pulse lengths and pulsation frequencies. These experiments were undertaken for different rock types. The observed rock damage was then used to construct an explanatory model of the mechanisms of rock fracture.

The breakage mechanism was found to be controlled by the number of water pulse impacts and by the duration of stagnation water-pressure on the target. The successive high-energy impacts of the water pulses were found to create localised fracture zones in the vicinity of the impact surface. These impacts also initiated fatigue in the target, introducing micro-structural damages. The initial impacts of water pulses created a damaged area at the point of impact. The stagnation pressure from the water flow supplied the crack opening pressure, which controlled the crack opening process and thus affected the development of the failure zone. However, crack growth could be interrupted by energy dissipation and by toughening mechanisms. It was found that effective rock-breakage depended upon the physical properties of the target rock, in particular the brittleness, and that, ideally, the length and frequency of the water pulses should be tuned to accommodate these rock properties to optimise the rock-fracture process.

**Keywords**
Pulsed water jet, rock breakage, experimental study, computational analysis, pulsation frequency, pulse length, and impact pressure measurement.
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1 Introduction

The use of water jets for rock cutting in mining operations is a centuries-old technology. Typically low-pressure, high-volume jets were used to erode weak rock, which was then sluiced for minerals separation and further processing. There are few mines today where this approach is still used. The use of high-pressure, low-volume water jets to cut rock has been seriously discussed since the 1960s (Farmer & Attewell 1965). This work was extended in the 1970s when jets were used to assist mechanical tools in rock cutting operations (Hood 1976).

High-pressure water jets, with their high power intensity, low reaction force on the nozzle holder, simple machinery, and minimal tool wear are attractive for niche cutting and machining applications in manufacturing and, today, there is a substantial industry that supplies high-pressure cutting systems to this industry. Although, in principle, the same advantages apply to rock-breakage in the mining and civil engineering industries, to date high pressure water jet rock-cutting systems are used only in rare circumstances in these industries. This is despite considerable efforts by many researchers over several decades to develop feasible and economically attractive water jet breakage systems. Extending the use of high-pressure water jets to breaking hard rock in surface and underground mining applications still requires significant improvements in jet cutting or jet breakage performance.

Experimental studies and practical applications, under the same jet pressure conditions, show that rock breaking efficiency can be significantly improved by optimising the distribution of the jet energy in both time and space (Ni, Wang & Du 2011). Pulsed water jets have been shown to be particularly attractive as a rock breakage tool (Foldyna et al. 2007; Nebeker 1987; Vijay, M. M. 1994). The mechanism of rock-breakage using pulsed water jets is complex and poorly understood. This is a key factor that has limited the wider uptake of pulsed jets as a rock-breakage method.

1.1 Problem statement and aim of the thesis

Rock-breakage is, arguably, the most important step in the mining process. Poor blasting practice produces large boulders, which are difficult and expensive to handle, particularly in underground cave mining operations. Some of the challenges in dealing with oversized rock are illustrated in Figure 1-1.
Blasting and heavy impact hammers are the main techniques currently used on mine sites to fracture oversized boulders. Both of these methods are problematic. Blasting can interrupt mine production and, in underground cave mines, is difficult to achieve and is time consuming. Impact hammers are cumbersome and cannot be used in situations where boulders are not readily accessible. For these reasons, CRCMining has been investigating the potential use of pulsed high-velocity water jets as a more effective method for rock boulder breakage. Pulsed water jets can deliver high power intensity stresses into the rock. The reaction force on the nozzle holder is low, so that a lightweight, flexible apparatus can be employed.

Preliminary research at CRCMining has demonstrated that pulsed jets are able, within a few hundred seconds, to routinely break large (~1m³) boulders of competent hard rocks such as granite, monzonite and greywacke (Figure 1-2).
Further research has also been conducted worldwide using pulsed water jets to investigate the effect of operational parameters such as: nozzle diameter, standoff distance, pulse frequency and jet pressure on rock breakability (Agus et al. 1993; Leach et al. 1966; Vijay, M.M., Remisz & Shen 1993). There is, however, only a limited understanding of the breakage mechanism and this makes
it difficult to improve the efficiency of the system. There are many fundamental questions, which have remained unsolved, such as:

- What is the type and amount of the applied energy on rock from the impact of a water jet pulse?
- How does the geometry of the pulse (length and diameter) affect the possible damage?
- What is the role of pulsation frequency on the quality of fracture and is there any optimum effective frequency for a rock type?
- Where does the governing fracture initiate?
- Do the induced stress waves, which are due to the dynamic nature of loading applied by pulsed water jets, play a significant role in breaking the samples or it is just as a result of the local hydrodynamics?
- Do the sequential impacts cause a fatigue phenomenon in the target?
- What is the dominant breakage mechanism? Is it erosion or tensile failure such as spalling and hydro-fracturing?

The scope of this research was limited to the investigation of the rock breakage mechanism using pulsed water jets. The characteristics of the water pulses are directly related to the methods employed for their generation. Since the magnitude and duration of the stress that is applied by a water pulse is controlled largely by its size (pulse diameter and length) and quality (coherence of the water pulse), this research initially aimed to investigate the formation of a water pulse using a simple water-filled chamber and an impacting technique. The quality of the produced water pulse was analysed using a high-speed video technique, and the magnitude of the induced stress from the impact of such pulse in a target was studied experimentally. The goal was to develop an understanding on the quality of the generated water pulses.

Since, however, a pulsed water jet is a series of discrete water pulses, the pulse length and the separation distance between two sequential pulses are important in the efficacy of the rock breakage mechanism. This research thus aimed to identify the role and relative importance of these parameters - pulse length and pulsation frequency, on the rock fracture process. The goal was to predict the appropriate jet parameters for breaking rock.
2 Formation and characteristics of water pulses

The development of practical methods for producing high-energy water pulses has always proven difficult. At one extreme are the water cannons, which provide highly energetic but single pulse impacts on the target (Edney 1976) and at the other extreme are the very high-frequency and low-energy pulsed jets, introduced by Vijay (1994), which are formed using an ultrasonic transducer upstream of the nozzle. These ultrasonically-formed jets have been developed further by Foldyna et al. (2004). Between these extremes are the so-called self-modulated jets. These use an organ pipe structure upstream of the nozzle to induce waves in the flow stream. The air drag causes the continuous jets to break up into a series of pulses when these jets exit the nozzle. These were first described by Nebeker (1976), and further developed by Chahine et al. (1983). Only the low-energy ultrasonically formed jets have found a widespread use as a practical device.

The characteristics of the water pulses are directly related to the methods employed for their generation. This research set out to understand the production of a single high-energy water pulse generated using a water-filled cylindrical chamber with a piston at one end and a centrally-located nozzle mounted at the other end. This method has been quite well-known for generating high velocity water pulses (Rehbinder 1983). In this system, the cylinder axis is vertical with the nozzle at the bottom and with the piston resting on the water surface. The water pulse is generated when a hammer is used to impact the piston. See Figure 2-1.

![Figure 2-1: A schematic view of the water-filled chamber, the piston and the hammer (not to scale)](image)

The research sought to highlight the key variables that influence the efficacy of generating water pulses with the aim of maximising the efficiency of these types of systems. This work was divided
into two parts: an analytical study, which investigated the possible arrangements of the design of the apparatus with the goal of determining the most efficient arrangement, and an experimental study, which built and tested the selected design. Later additional theoretical studies were conducted in order to determine whether further refinement of the model was justified or required.

2.1 Formulation of pulse formation

The pressure dynamics inside a water-filled cylindrical chamber that was impacted by a hammer-piston arrangement was studied. A theoretical and computational model was developed to explain both the impact mechanism and the phenomenon of pressure build-up in, and release from, the chamber. The problem to be solved was to calculate the changing water volume in the chamber with a moveable boundary (the piston) and with water discharging through the nozzle. The equations of continuity and conservation of mass were applied to relate the movement of the piston to the discharge from the nozzle. It was assumed that the flow inside the nozzle and the chamber was at quasi-steady-state and one-dimensional, and the water was inviscid and compressible.

This model postulated that immediately after the collision of the hammer and the piston, as soon as the piston starts moving, the water inside the chamber compresses and stores energy. The pressure in the chamber rises, triggering water discharge from the nozzle. The piston slows and eventually stops as the water approaches a maximum pressure, determined by water’s bulk modulus. This point corresponds to the maximum attainable pressure at the peak compressibility value. From this moment, the compressed water expands elastically, and releases the stored energy, lowering the pressure and reversing the direction of the piston. At this point, depending on the system design, a second collision will often take place between the hammer and the piston. This causes the piston to change direction and to recompress the water inside the chamber. A second peak pressure is then recorded, the magnitude of which is related to the compressibility of the remaining water volume in the chamber.

The product of the model was a formulation that predicted the pressure history within the chamber. It was solved for different combinations of the hammer and piston masses in order to find the optimal combinations of masses, keeping the nozzle diameter and the water column height unchanged. The model was next used to examine the effect of the height of the water column on the history of the pressure build-up inside the chamber. Figure 2-2 compares the predicted pressure history inside the chamber using nozzles of different sizes. The maximum peak pressure is the greatest (200MPa) for the blocked chamber (with a nozzle diameter of zero) and is the lowest (165MPa) for the 4.02mm nozzle diameter.
Figure 2-2: Pressure history inside the chamber for different nozzle sizes- Analytical model for quasi-steady-state flow

Figure 2-3 also compares the velocity of discharge at the nozzle exit for all five of the nozzle sizes examined. These graphs follow the same pattern as the pressure histories with the highest peak velocities of 500m/s for the 1.02mm nozzle diameter, and of 460m/s for the 4.02mm nozzle diameter. Knowledge of the velocity of discharge at the nozzle exit allowed the instantaneous volume of the water ejected from the nozzle to be easily determined by multiplying the cross-sectional area and the nozzle discharge coefficient at the corresponding velocity values.

Figure 2-3: Discharge velocity histories at the nozzle exit for different nozzle sizes- Analytical model for quasi-steady-state flow
2.2 Validating experiments

The efficient piston, hammer and chamber system that was defined from the model was built for experimentation. See Figure 2-4. The hammer was dropped from a height of 6m onto a piston that was initially resting on the surface of a water-filled cylindrical chamber and the pressure history within the chamber was recorded during the event using a dynamic pressure sensor that was mounted flush on the inside wall of the chamber. The experiments were carried out for different nozzle sizes (1.02mm, 2.08mm, 2.98mm, 3.43mm and 4.02mm) and repeated to obtain consistent pressure profiles.

The experimental observations confirmed the behaviour observed from the model. Data from the pressure sensor mounted in the cylindrical chamber also showed two peak values, the second being lower than the first. The magnitude of these maximum pressures decreased with increasing nozzle size. The first peak pressure for the 1.02mm nozzle diameter had a magnitude of 200MPa; this value was reduced to 170MPa for the 4.0mm nozzle diameter. An excellent correlation was found between the theoretical pressure profiles and the recorded experimental data, thus validating the model (Figure 2-5).
Figure 2-5: A comparison of the recorded and the computational pressure profiles for different tested nozzles. The solid line in all graphs is the predicted theoretical pressure profile.

The theoretical model for calculating the history of pressure dynamics in the chamber was on the basis of a quasi-steady-state flow assumption. Although there was a good agreement between the result of this model and the experimental values of the output pressure, there was a concern that this flow assumption may have oversimplified the problem. A more complex, unsteady-state flow model was then developed. In this new model, the concept of equivalent nozzle length $L_e$, which had been previously introduced by Rehbinder (1983), was employed. This equivalent length factor, which takes into account the inertial effect of the nozzle, was found to be influential in the resultant pressure and particularly in discharge velocity gradients. The additional complexity of the unsteady-state flow model was found to be unwarranted, given the sensitivity of this unsteady-state system to
the value of $L_e$, and the fact that the available methods for calculating the value of $L_e$ were imprecise. The quasi-steady-state flow approach was thus preferred.

Sudden pressure changes, which were manifested as sudden very sharp spikes in the experimental data, prompted further investigation of the pressure build-up in the chamber based on the interactions of the stress waves in the whole system - in the hammer, in the piston and in the water column. A two-step process was used to develop a model using the assumptions of rigid and elastic bodies. The pressure of the water at the bottom of a closed chamber was determined. Good correlation was found between the result of the model and the experiments.

3 Integrity of generated water pulses

The magnitude and duration of the stress applied by a water pulse striking a target is controlled largely by the pulse size (diameter and length) and the pulse quality (coherence and density). The coherence of the water pulse that was generated by the hammer-piston impacting system was of concern in this study. If repeated shock reflections within the chamber were transmitted or were carried into the nozzle’s internal geometry, this could have caused the emerging jet to pulsate.

The formation and the impacting phenomenon of a pulsed water jet occur too fast to be observable with the naked eye. The coherence of the water pulse produced with the described water-filled chamber through a $1\, mm$ diameter nozzle was thus studied using a high-speed video technique. The aim was to investigate the influence of any induced stress waves within the chamber on pulse coherence and gain a better understanding and insight of jet formation and pulse consistency.

Two sets of experiments were conducted: the first set was at high-resolution and low frame-rate to investigate the change in the coherence of the pulse due to air drag; the second set was at low-resolution and high frame-rate in order to focus on the formation and on the alteration of the shroud of the droplet spray covering the core of the jet.

The high-speed video demonstrated noticeable sections with density differences and fairly regular separations in the pulse stream at the early stage of the discharge (Figure 3-1). This was explained by the presence of travelling stress waves exiting through the liquid inside the nozzle. The results suggested that there was little if any effect of shock reflections inside the nozzle. The velocity variance within the pulse, which was associated with the pressure dynamics in the chamber, was suggested as the main cause of breaking the water pulse into sections of different shape and velocity.
The high-speed photographic study also indicated the formation of a large shroud of droplets during the first 200μs of the discharge, which then eased for the last 150μs of the discharge (Figure 3-1 and Figure 3-2). The model that was developed showed that, during this early time period, the velocity of the packets of water exiting the nozzle continuously increased, meaning that the later packets had a higher velocity than the packets ahead of them. This intense droplet shroud during this time was then attributed to the interaction of water packets, causing jet break-up and creating a cloud of mist in front. The part of the jet that followed was a perfect cylinder with a diameter close to that of the nozzle diameter. This cylindrical part of the jet travelled a distance of ten nozzle diameters.

As the water particles exited nozzle, forming the water pulse, a relatively large mass of water was created (frames 11 to 14 in Figure 3-2). Although this mass has a rounded front and looks very dense, its coherence was questionable. It possibly contained more atomized liquid than the core jet. The velocity of this pulse mass was calculated at about 480m/s based on its displacement within frames. These results revealed that the generated water pulse most possibly was not a single coherent jet; it was rather broken into discrete sections.
Theoretical models were also developed to determine the shape of the core of the jet on the basis of the interaction of the water packets with different velocities. The effect of air drag force was neglected in these models. The possibility of merging water packets of different velocities to form a bigger packet was shown to be unlikely. Alternatively, the theory in which the faster water packet smashed into and destroyed the slower one achieved very acceptable results. The core of the pulse was found to have a cucumber shape (Figure 3-3) that was covered by a shroud of droplets, which were formed from the dispersion of the water packets.
The model also determined that only 20% of the jet was disturbed thus forming the droplet shroud whilst the rest stayed in the core. This supported the view that the main part of the jet stays as an intact core at short distances from the nozzle and that only a small portion of the jet volume transforms to the shroud of drops.

4 Impact-induced stress measurement

The effectiveness of the generated water pulses using the described water-filled chamber in striking a target was next investigated. Upon the impact of a high velocity water pulse, a short-duration high-intensity impulsive stress described as water hammer pressure $P_w$ is applied on target. This is the result of the compressible behaviour of the water against the target at the initial stages of the impact. Despite a largely theoretical understanding of the impact phenomenon, the magnitude of the impact force developed from water impact and the resulting deformation of the surface are not fully understood. This is mainly due to the transient nature of the phenomenon and to the difficulties in measuring this force because of the very short impact time (Grinspan & Gnanamoorthy 2010).

Capturing the very short duration water impact event at a very low noise level was the main challenge in this research. This very short event required a sensor with a sufficiently quick response time to record enough data points before the water hammer pressure ceases. Figure 4-1 shows a
possible view of the expected waveform of the generated stress wave in the target from the impact of a single water pulse. The slope angle of the rising curve $\theta$ depends on the “instantaneous” material response; whereas the maximum attainable stress is controlled with a viscous relaxation in the sensor and in the target until equilibrium is reached (Asay et al. 1994). $\theta$ is larger for steel than for polymers due to its faster response speed.

![Figure 4-1: Expected stress wave waveform induced from the impact of a water pulse in a target](image)

The duration of water hammer pressure $t_r$ in Figure 4-1 is largely influenced by the diameter of the water pulse if the length of the pulse is longer than its diameter.

A PVDF shock gauge was used to capture the stress induced within a target by the water hammer and the stagnation pressures when a high velocity water pulse was directed normally against the target. The PVDF film provided a direct measure of stress-derivative or stress-rate signals of a few nanoseconds duration. Comparison of the measured data with the expected values from the theory then determined the coherence and shape of the core of the water pulse.

In these experiments, the PVDF gauge was embedded between two pieces of the target material. As the induced stress was conveyed through the top piece of the target a stable waveform developed that its profile was directly related the shape of the water pulse. The use of this technique further resulted in preserving the PVDF gauge from the violent impact of the water jet.

The acoustic impedance of the target material was matched with that of the PVDF film to avoid any dispersion of the input energy. Kel-f was selected as the suitable material for the target. Kel-f is a
brand name for a fluorocarbon-based polymer called PolyChloroTriFluoroEthylene. This material has similar acoustic impedance as the PVDF material.

The target compound (the Kel-F discs and the embedded PVDF gauge) was secured onto a steel plate. The backing Kel-F piece was located within the plate, supported on its built-in shoulders, and the top Kel-F piece was maintained in place by the use of a locating ring, which was fixed on the plate using four equally-spaced screws. See Figure 4-2A. The clamping of the target with the support of the locating ring compressed the pieces, thus assuring that intimate contact was achieved for all materials.

The steel plate was mounted on a rigid frame of the water jet apparatus using a rigid holder. See Figure 4-2B. This holder was designed to have no deflection from the impacting force. The overall view of the test set-up is illustrated in Figure 4-2C. The standoff distance (the distance from the top surface of the Kel-F to the nozzle head) was varied from 100mm to 120mm from one test to the next.

The schematic view of the water jet apparatus in relation to the impact pressure measurement set-up is illustrated in Figure 4-3. The water pulse was generated by dropping a hammer from a height of
In addition to the PVDF gauge, measurements from an accelerometer, mounted on the piston, and a PCB pressure sensor, located inside the water chamber, were obtained (Figure 4-3). The accelerometer monitored the movement of the piston and recorded the instant of impact, whilst the piezoelectric pressure sensor monitored the pressure history inside the water chamber. The measurement of the PVDF gauge was synchronised with the accelerometer and the piezoelectric pressure sensor.

The response of the PVDF gauge was analysed with respect to the measurements from the PCB pressure gauge, reflecting the history of the pressure dynamics in the reservoir (Figure 4-4). The time delay between the initiation of the pressure dynamics inside the chamber and that of the PVDF gauge response was used to determine the velocity of the front of the water pulse. This was found to be equal to 264 m/s. This impact velocity could theoretically generate a water hammer pressure with a magnitude of 275 MPa and a stagnation pressure equal to 35 MPa.

The PVDF shock response to the impact of the single water pulse (Figure 4-4) showed three main peaks. The study of this signal indicated three discrete impacts that the peak magnitude of these impacts exhibited an increasing trend with time; the first peak having the lowest stress value and the
third peak having the highest value. This, indeed, supported the result of the modelling and experimental work whereby the faster packets of water, which exited the nozzle later in the impact sequence, disaggregated the front section of the main pulse. It also confirmed that the generated single water pulse had broken into three discrete sections.

Figure 4-4: Comparison of the signal from the PVDF gauge with the signal from the PCB pressure sensor, which represents the pressure dynamics in the chamber.

Figure 4-5 illustrates the stress waveform induced from the initial impact of the water pulse. The peak stress reaches a magnitude of 33MPa and then starts declining after 450\(\mu\)s. The positive stress lasts for 1\(\mu\)s and is followed by a drop to -10MPa. The stress, after some fluctuations, stabilises at about 1.37MPa. The data beyond this window was disregarded as it had been contaminated with interference from the reflected waves.

Figure 4-5: Associated stress on Kel-f from the impact of the water pulse.
The measured profile of the stress variation in Figure 4-5 was found to be very similar to the stress profile that was generated by the explosion of cavitation bubbles and/or by the impact of the spherical droplets (Grinspan & Gnanamoorthy 2010). This was a representative of the water pulse impact where the pulse length is similar to its diameter. The magnitude of the peak stress in the recorded data (33MPa), which was the result of the initial impact of the water pulse at the velocity of 264m/s onto the Kel-F disc, was of the same order as the expected value (29MPa), which was analytically determined at the location of the PVDF gauge and using the theory of elasticity. The associated stress from the stagnation pressure was, however, lower. This was explained by the energy that had been consumed to create the local failure on the impact surface of the Kel-F (Figure 4-6).

5 Rock breakage with multiple water pulses

The research work described thus far has dealt with the formation and characteristics of a single water pulse. An effective pulsed water jet generally consists of a sequence of rapid water pulses. Effective rock breakage by a pulsed jet depends not just on the shape, velocity and impact stresses imposed by an individual pulse. In addition, and just, or even more importantly, rock breakage depends on the pulse length and the separation distance between 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 can be used to design the most efficient pulsed water jet apparatus.

The contribution of multiple impacts of a pulsed water jet on the rock breakage process was analysed by conducting an experimental study using an external-flow-interrupted pulsed water jet
device (Figure 5-1A), where the rotation of a slotted disc at high speed in front of the continuous jet emerging from a nozzle, was used to generate discrete water pulses. The pulse length and pulsation frequency were varied by changing the number and the width of the slots in the disc and by changing the rotational frequency of the disc (Figure 5-1B).

The influence of the jet velocity, the pulse diameter and the standoff distance were kept constant for all the experiments in pursuit of investigating the sole effects of pulse length and pulsation frequency on the breakage of different rock types. Granite and marble samples with diverse mechanical and physical properties were used in these experiments (Table 5-1).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Granite</th>
<th>Marble</th>
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<tbody>
<tr>
<td>Bulk Density (kg/m3)</td>
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<td>UCS (MPa)</td>
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<td>BTS (MPa)</td>
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<td>Secant Young Modulus (MPa)</td>
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<td>Poisson’s ratio</td>
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<td>Fracture toughness (MPa, M0.5)</td>
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<td>Longitudinal wave velocity (m/s)</td>
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<td>Shear wave velocity (m/s)</td>
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<td>Dynamic Bulk Modulus (GPa)</td>
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<tr>
<td>Acoustic Impedance (MPa.s/m)</td>
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<td>15.16</td>
</tr>
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</table>

Two levels of variability for pulse length and 3 levels for pulsation frequency were selected in order to minimise the number of test trials. A 2-level full factorial design method (Box, Hunter & Hunter...
1976) with 3 factors or independent variables (rock type, pulse length and pulsation frequency) was used to create the test matrix. Table 5-2 summarises all the independent variables and their level of variations in the experiments.

<table>
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<th>Independent Variable</th>
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<td>Confining pressure</td>
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<td>Exposure time</td>
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<td>Standoff distance</td>
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<td>100</td>
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<td>Pulse length</td>
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<td>458, 888</td>
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<tr>
<td>Frequency of pulse</td>
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<td>53, 106, 212</td>
</tr>
<tr>
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<td>Granite, Marble</td>
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</tbody>
</table>

The dependent variable in the experiments was the amount of damage caused in the rock samples. The main challenge in this regard was to control the fracture so that one test could be compared with another. This was addressed by using core samples of competent (no obvious visible fractures) rocks that were confined laterally during the experiments as the jet impacted on the cylinder end. The samples were 55mm in diameter with height to diameter (H/D) ratio of 2.4. The confinement was provided by placing the specimens inside a Hoek Cell - a device that is conventionally used for triaxial testing of rocks in the laboratory (Figure 5-2A). A stiff frame was designed and manufactured to hold the Hoek Cell firmly in front of the jet nozzle (Figure 5-2B).

![Figure 5-2: Schematic view of the A. sample inside the Hoek Cell and, B. Hoek cell holder frame](image)

The exposure time of the samples to the water jet impacts was controlled using a gate installed on the Hoek cell holder frame (Figure 5-3). Since the confining pressure and the exposure time both...
affected the breaking ability of the pulsed water jet, these two variables were kept constant and identical for all the experiments. A static pressure gauge was mounted on the Hoek cell (see Figure 5-3) to record the possible variance in the confining pressure during the experiment.

![Figure 5-3: The Hoek cell test, overview of the frame and instrumentation devices](image)

The independent variables (pulse length and pulsation frequency) were changed by using perforated discs of various slot numbers and slot lengths (Table 5-3) and the experiments were carried out on marble and granite to study the breakage mechanism. The local failure, as well as the internal breakdown were of interest and thus monitored.

### Table 5-3: Pulse length and pulsation frequency for different discs

<table>
<thead>
<tr>
<th>Disc No.</th>
<th>Slot width mm</th>
<th>Spoke width mm</th>
<th>Number of slots</th>
<th>Pulsation frequency (Hz)</th>
<th>Pulse length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>14.9</td>
<td>150.1</td>
<td>4</td>
<td>53</td>
<td>458</td>
</tr>
<tr>
<td>3</td>
<td>25.7</td>
<td>139.2</td>
<td>4</td>
<td>53</td>
<td>888</td>
</tr>
<tr>
<td>5</td>
<td>14.9</td>
<td>67.6</td>
<td>8</td>
<td>106</td>
<td>458</td>
</tr>
<tr>
<td>6</td>
<td>25.7</td>
<td>56.7</td>
<td>8</td>
<td>106</td>
<td>888</td>
</tr>
<tr>
<td>8</td>
<td>14.9</td>
<td>26.4</td>
<td>16</td>
<td>212</td>
<td>458</td>
</tr>
<tr>
<td>9</td>
<td>25.7</td>
<td>15.5</td>
<td>16</td>
<td>212</td>
<td>888</td>
</tr>
</tbody>
</table>
Local damage was characterised as the tangible breakage that was visible with naked eyes at the impact surface of the target. It was studied by cutting the top off the sample at 30\text{mm} from the impact surface and then by splitting this severed piece in half with the fine cut passing axially along the cavity created by the jet. The surficial cavity, its shape and depth, and the major surface and sub-surface cracks along with their possible propagation paths below the damaged zone were then analysed. The directions of the extended cracks were a good indication of the stress distribution and variation within the target from the pulsed water jet. See Figure 5-4 and Figure 5-5 as an example of these investigations for granite and marble targets respectively. The depth of the surficial damage cavity were also analysed with respect to energy that was consumed (Figure 5-6).

Figure 5-4: Local cavity and cross section of sample Gr2 – F=53Hz and L=888mm

Figure 5-5: Local cavity and cross section of sample M5 (fine-grained) – F=53Hz and L=888mm
The internal damage, on the other hand, was an increase of micro-crack density within the rock sample after being subjected to pulsed water jet impingements. This was attributed to fatigue-related failure. Since there was a direct relation between the internal imperfections of materials and their intrinsic attenuation properties (Tompkins & Christensen 2001), the comparison of the wave related quality factors ($Q$ values), a form the wave attenuation capability, appeared to be an appropriate way of evaluating the damage as internal flaws and micro-cracks. The extent to which fatigue damage occurred in rocks was thus studied by examining the shear wave related Quality factors $Q_s$ of the specimen before and after being subjected to the pulsed jets of various properties. The through-transmission ultrasonic testing method was used to determine the attenuation property of the rock samples. Figure 5-7 illustrates the results of these studies.

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**Figure 5-6**: Total consumed energy versus total depth of the damage cavity

**Figure 5-7**: Variation of $Q_s$ (Quality factor for shear wave attenuation) with pulsation frequency and pulse length in marble samples: A. Marble, B. Granite
The analyses of these experimental studies demonstrated that both the pulse length and the pulsation frequency interactively contributed to affect rock breakage process. Depending on the rock type, one of these factors played a more important role than the other in creating failure in a rock sample. The pulse length became more important as the surficial damage (resulted from spalling and visible cracking) deepened. Pulsation frequency, on the other hand, was found to be the key parameter causing internal breakdown (micro-structural damage) in the rock samples.

An increase in pulse length corresponded with an increase in the duration of hydrostatic pressure from water flow. The deeper cavities produced by the longer pulses provided evidence for this. Also, the longer pulses applied a larger crack-opening pressure over a longer time which developed cracks further than the shorter pulses. The surface of the cavity was found to be much smoother after longer pulses indicating that more erosion-type damage had occurred. Furthermore, the samples with the smaller grains showed more resistance to the water jet pulses than the large-grained crystallised sample. This behaviour was observed from marble samples with different grain structure.

Pulsation frequency directly influenced the failure zone under the impact surface. It was discovered that the damaged zone was not limited to the local impact area; internal cracks were observed. This type of failure was attributed to the interaction of the stress waves which resulted from the pulsed water jet impacts with the micro-structure of the rock samples such as micro-cracks, flaws and grain boundaries. The internal cracks were found to incline or propagate in the direction of the major principal stress trajectory.

An increase in the pulsation frequency with the shorter pulses increased the depth of the cavity. This was not the case, however, for the longer pulses. The higher the frequency for longer pulses, the more likely was the possibility of spalling. Spalling took place at all three pulsation levels but it happened much sooner at 106Hz, thus creating thinner flakes. Overall, the thicknesses of the spalled chips were greater for the shorter pulses. This was also attributed to the greater crack-opening pressure applied by pulses of longer lengths.

An increase in the spacing between the short pulses generally reduced the depth of the cavity. As the length of the pulses increased, an optimum spacing came into play where, above and below this level, the quality of the created damage, as of both surficial and internal failure, was reduced.
The individual and interactive effect of the pulse length and pulsation frequency on the failure process of a rock target varied with the physical properties of the rock especially with its brittleness. A promising correlation was found between the brittleness index factor of the rock samples and their response behaviour to pulsed water jet impacts. Pulsation frequency was identified as the key influential factor on the failure of very brittle rock samples. In less brittle material, however, as the frequency of pulsation increased, the pulse length became an essential factor.

In summary, the pulsation frequency was found responsible for creating a failure zone directly under the impacted surface. The pulse length, however, controlled the development of this failure zone by influencing the crack propagation process. The latter influenced the length of time that high pressure was applied to drive the crack propagation process. Hence longer pulses were required to propagate cracks as the depth of damage increased.

6 Conclusions

The impacts from high-velocity water pulses apply substantial amounts of energy onto a rock target surface which directly results in rock damage and rock breakage. These impacts also induce stress waves within the target. High-energy impacts and the interaction of the release waves (the reflected tensile waves from interfaces) within the body and at the surface of the target were found to be responsible for creating localised fracture zones in the vicinity of the impact surface. The pulsation frequency, by controlling the number of the impacts, is responsible for creating this failure zone. It was discovered that successive impacts initiate fatigue in the target by introducing micro-structural damage which contributes significantly to the ultimate failure.

The length of the water pulses was found to control the hydrostatic pressure that was induced in the cracks and cavities which had been created by the impact of previous water pulses. This provided the crack-opening pressure thus driving crack propagation, thereby affecting the development of the failure zone. However, crack growth can be interrupted by energy dissipation and by toughening mechanisms. The latter includes crack shielding, crack deflection, crack arresting, crack bridging and crack progression through the rock grains. This is where the appropriate design of operational factors such as pulse length and pulsation frequency can play a significant role in improving the failure process of the rock.

The static and dynamic failure behaviour of the rock, as well as its brittleness index were found to be important characteristics when selecting a pulsed water jet with a suitable pulse length and pulsation frequency.
These findings are based on the assumption that the water pulses are coherent and well-separated. It must be recognised that the method employed for the generation of water pulses is very influential on the shape and on the quality of the pulses. The energy delivered by a water pulse that is produced using the impacting technique and a water-filled chamber showed that the developed water pulse stream is broken into sections of different velocities. The stress within the target that is struck by such a pulse clearly confirmed the occurrence of the water hammer pressure. The duration of the water hammer pressure lasted for 1μs. The stress induced by the stagnation pressure was influenced by the interference of the release waves.

This research successfully achieved its stated goals but some aspects of the rock-breakage mechanism subjected to a pulsed water jet needs more study. The role of the different factors such as pulse length, pulsation frequency, induced stress waves and dynamic fatigue phenomenon in failure of rocks has been identified, but the research still cannot specifically recommend an ideal pulsed water jet with certain operational parameters for the most effective breakage of different rock types. This is mostly due to the fact that the physical properties and the failure behaviour of specific rock types affect the efficacy of the pulsed jet.

7 Reference


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