# High pressure abrasive water jet for excavation purpose: a tridimensional approach for cutting strategy

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## Abstract

High pressure abrasive water jets (HPAWJ) are an emergent excavation technology. Despite being used for several applications since the nineteenth century, it is only in recent decades that this excavation purpose has been considered. This is the result of evolution in high pressure pump technology and parameter investigation. Special highlight should be given to optimization works which improve knowledge about the main parameters. However, studies usually neglect the importance of HPAWJ cutting strategies, and only consider bidimensional approaches as options for nozzle movement. This article analyzes and proposes an operational cycle based on a tridimensional approach for HPAWJ. Higher removal rates and lower energetic consumption are expected in comparison with traditional strategies.

**Keywords:** high pressure abrasive water jet, cutting strategy, removal rate.

## 1. Introduction

### 1.1 High pressure abrasive water jet (HPAWJ) for excavation purposes

The considerable amount of power carried by high pressure abrasive water jets (HPAWJ) has made possible their use in nearly all areas of modern industry, including the automotive and aerospace industries, construction engineering, environmental technology, chemical process engineering, and industrial maintenance (Momber and Kovacevic, 2012). One of the most challenging uses is related to oil drilling and mining technology which, due to the great variability of rock proprieties, has stimulated researchers in recent decades.

In Hood (1977), one of the first articles on the topic, the performance of drag bits with and without a combined water jet was investigated. The study concluded that it is possible to cut hard rock deeper and faster with a water jet at 400 bars. Years later Pritchard and Reimer (1980) confirmed that a drag bit assisted with a water jet could reduce the excavation force and disc cutter wear, improving the advance rate and cutter lifetime. Similar results were found by Ciccu and Grosso (2010). They affirm that water jet assistance is effective in improving the performance of mechanical tools.

Experimental analyses were focused on disc cutter performance assisted by high pressure water jets in Kouzmich and Merzlyakov (1983), Fenn *et al.* (1985), and Ciccu and Grosso (2014). While in Fenn *et al.* (1985), four low-pressure jets of water were utilized (two on each side of the disc) to remove the crushed material after its formation and reported was a 40% reduction of thrust and rolling force upon the disc cutter, Kouzmich and Merlyakov (1983) and Ciccu and Grosso (2014) investigated the feasibility of water jet assistance for disc cutter assistance. Santos *et al.* (2018.a) and Santos *et al.* (2018.b) have a different approach. While the first article investigated the application of HPAWJ as a main excavation technology in tunnelling, in the second article, a tunnel boring machine concept which makes use of HPAWJ was proposed.

The development of a petroleum drill concept described in Maurer *et al.* (1973) was also an important step. The utilization of HPAWJ in petroleum drilling was quickly investigated and the introduction into the field was almost simultaneous. Solutions for stimulated oil fields have also been reported. The water jet technology has also been utilized for methane drainage in coal mines, especially in China since the nineties. A self-propelled nozzle that increased the drainage area in coal mining was proposed by Lu *et al.* (2015). A different approach has been followed by Lu *et al.* (2013). They proposed a drilling machine for coal mining that digs the rock in two stages, one with a water jet and another with mechanical enlargement.

## 1.2 Process parameters

The HPAWJ process is characterized by a large number of process parameters that determine efficiency, economy, and quality of the whole process. Generally, the process parameters in HPAWJ are divided into hydraulic parameters, cutting parameters, mixing-and-acceleration parameters, and abrasive parameters. Figure 1 shows a diagram with some of these parameters.

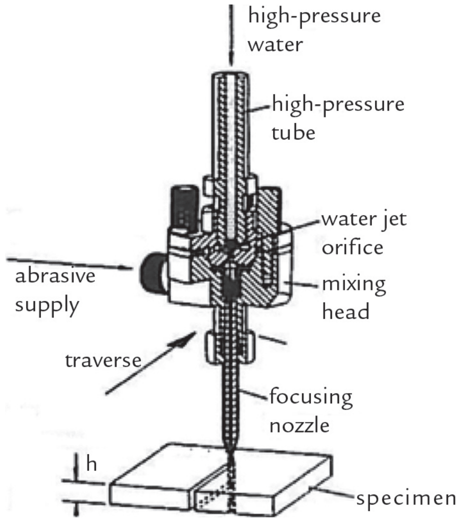


Figure 1
Some influence parameters over process performance. Highlight on cutting parameters (transverse rate, number of passes, stand off distance, impact angle and guidance nozzle) which define the cutting strategy.
Source: Adapted from Momber and Kovacevic, (1999).

According to Momber and Kovacevic (2012), the cutting parameters significantly affect the process performance. Their values define the cutting strategy. The main factors are:

• Transverse rate, (v): the transverse rate is probably the most important cutting parameter. It can be understood as nozzle velocity relative to the impacted material;

• Number of passes, ($n_p$): as the performance of HPAWJ reduces with cut depth, the strategy of multi-passes is very common. This parameter can be understood as the number of times that the water jet acts over the same area;

• Stand-off distance, (x): the distance between the nozzle and the impact material surface is defined as stand-off distance. As the axial and radial pressure shape of the water jet changes with its propagation, the stand-off distance parameter has significant importance about the performance process.

• Impact angle, ($\phi$): the impact angle can be described as the angle between the water jet center and the impact material surface;

• Nozzle guidance: the nozzle guidance can be understood as the path of the water jet during the cutting process. This path usually has the objective of bidimensional removal, and is not concerned about creating tridimensional bodies.

A typical relationship between the transverse rate, [mm/s], and depth of cut, [mm], for three types of material is shown in Figure 2. It is possible to note that the dependence is very significant for low transverse rates but different scenarios are observed at high transverse rates. In that condition, the depth of cut approximates a saturation value or even crosses the abscissas. This behavior can be explained by the reduction in the number of impacting abrasive particles and volume of water that penetrates the erosion site with an increase of transversal rate.

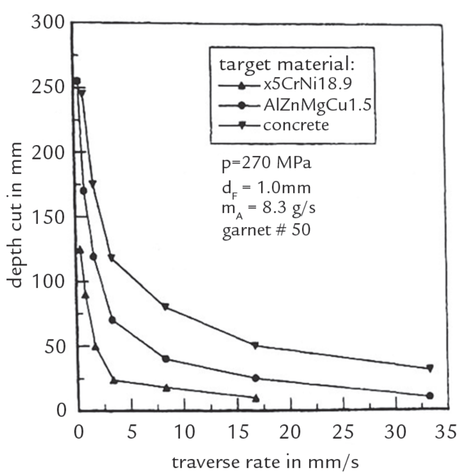


Figure 2
Influence of transverse rate over depth of cut for three materials. It is possible to note two different regions. One, with low transverse rate, for which the influence of this parameters is high and the other where the depth of cut approximates a saturation value.
Source: Adapted from Momber and Kovacevic, (2012).

A simple mathematical expression in Equation 1 describes the relationship between depth of cut and transversal rate. In this equation, while the constant $C_8$ is a negative number and usually lies between -0.4 and -1.0, the constant $C_7$ considers the influence of other process parameters. According to Momber and Kovacevic (2012), and Blickwedel (1990), a more accurate approximation can be described by Equation 2. In this equation, the constant $C_7$ depends on other process parameters.

$$h(v) = C_7 \cdot v^{C8} \quad (1)$$

$$h(v) = C_7 \cdot v^{-(0.86 + \frac{2.09}{v})} \quad (2)$$

As the performance of the HPAWJ process decreases with the increase of cut of depth, a multi-pass strategy is very common. Figure 3 plots a typical relationship between the number of passes and the depth of cut. Notice that there is almost a linear relationship in the beginning, but the progress drops at a certain critical number of passes, as shown in Figure 3(a). An optimum combination between the number of passes and the transversal rate exists that yields a maximum depth of cut and adds lines of equal energies in a number-of-passes diagram, as shown in Figure 3(b). According to Momber and Kovacevic (2012), this result is due to a balance between the impact damping and wall friction at a certain depth of cut. The difference between the measured depth of cut and the depth of cut obtained from an idealized linear relation between the depth of cut and the number of passes, $\Delta h_p$, estimates the amount of energy lost by this phenomenon.

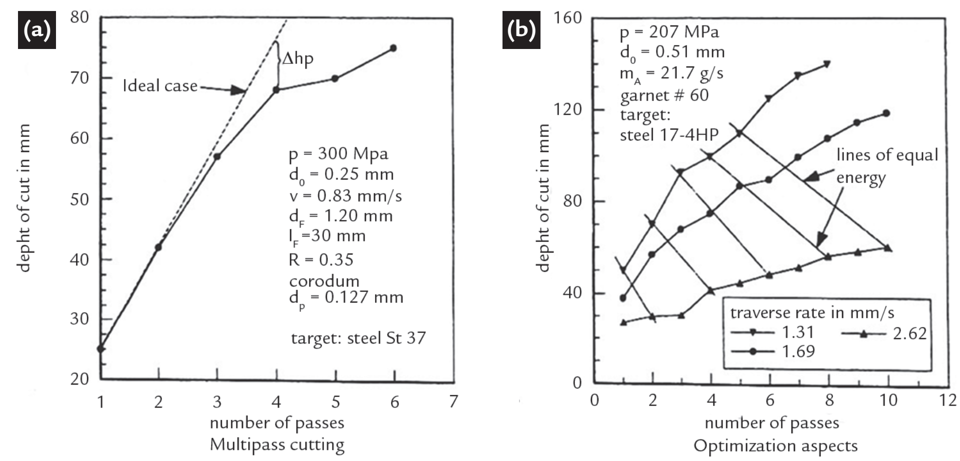


Figure 3
Influence of number of passes, $n_p$, over the depth cut. It is important to note that, due to damping and friction effects, the influence of the number of passes differs from the linear case by $\Delta h_p$ (left side) and an optimum energy number of passes exists (right side).
Source: Adapted from Momber and Kovacevic, (2012).

The stand-off distance has a significant influence over HPAWJ performance. According to Saunders (1982), Blickwedel (1990), Guo *et al.* (1994), Chung *et al.* (1992), and Kovacevic (1992), an almost linear decrease in the depth of cut is achieved with an increase of stand-off distance. Figure 4 shows a typical relationship between stand-off distance and depth of cut.

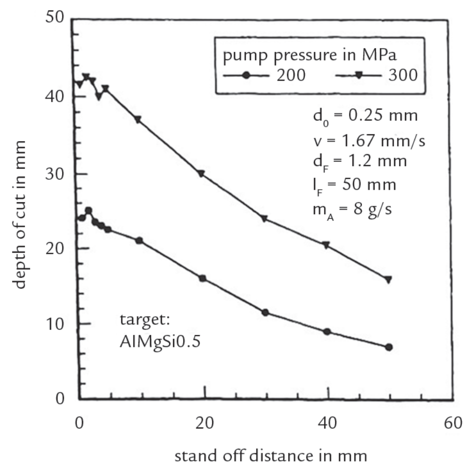


Figure 4
Influence of stand off distance for two pump pressure levels and one material. It is important to note the almost linear decrease of depth of cut.
Source: Adapted from Momber and Kovacevic, (2012).

In the same way, according to Momber and Kovacevic (2012), the impact angle has significant importance. For brittle materials, it is known from solid-particle erosion experiments that maximum erosion rates are found with an angle of 90 degrees. Figure 5 shows this tendency for abrasive water-jet cutting of several brittle composite materials.

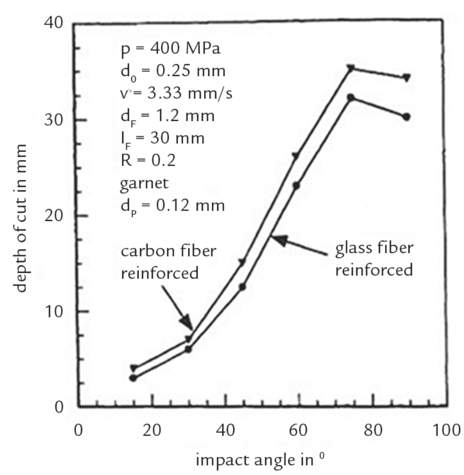


Figure 5
Influence of impact angle over depth of cut. An optimum value can be found between 80 and 90 degrees for brittle materials.
Source: Adapted from Momber and Kovacevic, (2012).

Finally, but of no lesser importance, the guidance nozzle is the path executed by nozzle during the cut process. As shown in Figure 6, the most common are transverse, rotation, and oscillation strategies. As can be noted in Figure 6, each one results in a different cut geometry.

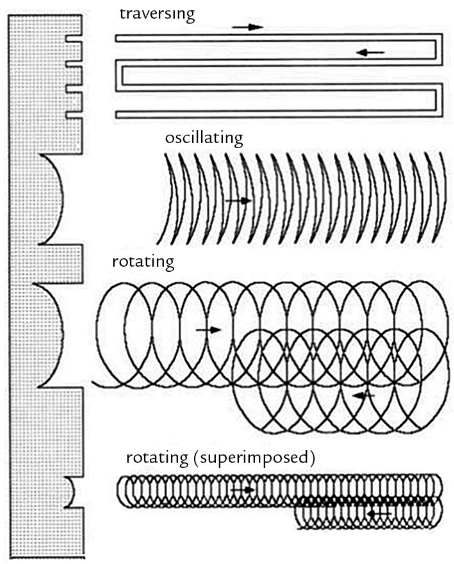


Figure 6
Mains guidance nozzle strategies
and their influence over the cut geometry.
Source: Adapted from Momber and Kovacevic (2005).

Comparative investigations about these types of movements have been performed by Kauw (1996) and Werner (1991). These authors demonstrated that oscillating and rotating nozzle carriers are more effective than simple traverse mechanisms for cementitious materials, as it is possible to note from Figure 7.

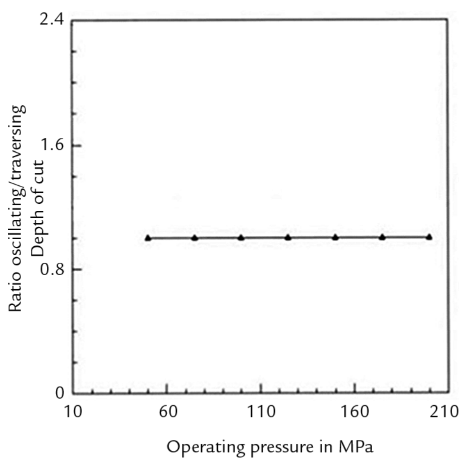


Figure 7
Comparative performance of oscillating and traversing strategies over depth of cut.
Source: Adapted from Momber and Kovacevic (2005).

## 2. Cutting strategy: tridimensional approach

The main objective of the cutting strategy is usually to execute the total disassembly of the rock, generating and focusing on maximizing the removal rate, and generating boulders that can be removed by other methods. This requires a high energy consumption with high pressure, large nozzle diameter, high abrasive rate beyond the high transverse rate, high number of passes, low stand-off distance, optimum impact angle and oscillation of the nozzle path.

An alternative is a tridimensional approach, focusing on maximizing the depth of cut with the main objective of creating tridimensional bodies with a sharp cut in the rock. This approach has potential to significantly reduce the energy consumption of the process. This can be achieved with high pressure, reduced nozzle diameter, low transverse rate, reduced number of passes, low stand-off distance, optimum impact angle, and a tridimensional nozzle path.

Figure 8 shows how a tridimensional approach can be executed in a tunnel excavation. First of all, it is necessary to make an annular cut with a thickness of 100 mm and a depth of 500 mm. This can be executed by a mechanical mechanism or manually with HPAWJ guns, as illustrated in Figure 8.b. The nozzle movement should be composed by oscillation followed by advance movement.

The second step is a set of vertical and horizontal cuts with smaller thicknesses but same depth of annular cut. The result is a set of small beams that can be transversely cut with HPAWJ apparatus, forming tridimensional bodies as shown in Figure 8.g and 8.h.

As the tridimensional approach does not dismantle all of the rock, the energetic consumption should be less than the bidimensional strategy. This same fact probably results in a high level of removal rate.

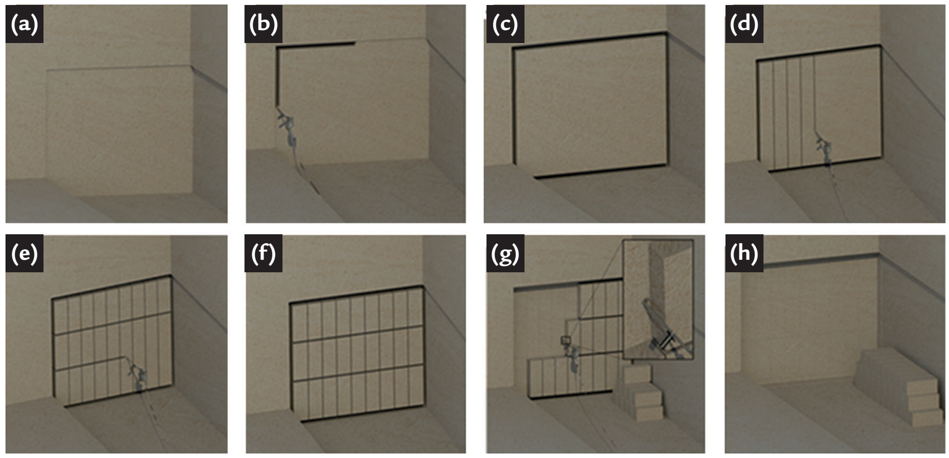


Figure 8
Tridimensional cutting strategy.

## 3. Conclusions

The performance of high pressure abrasive water jets (HPAWJ) is influenced by several factors, among them transverse rate, number of passes, stand-off distance, impact angle, and nozzle guidance have great importance. These parameters define the cutting strategy and usually have a bidimensional approach. An alternative is a tridimensional approach.

Focus was on maximizing the depth of cut with the main objective of creating tridimensional bodies, the operational cycle utilized traditional HPAWJ equipment to create a net of openings on the excavation front allowing, after transversal cut, the controlled dismantling of rock. This approach has potential to significantly reduce the energy consumption and increase the removal rate of the process.

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