Extended abstract

Rock cutting with high-pressure water jets

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Abstract: This article summarises the basic knowledge and the industrial experience concerning the application of high-pressure waterjet technology for the extraction of squared blocks in granite quarries. After a brief introduction of the state of art is given regarding the scientific fundamentals on the subject of rock disintegration mechanism and the main achievements resulting from past research efforts showing the problems faced by the sector, followed by an outlining of the industrial use and the main parts of the water jet system. Then attention is focused on the results of field experience highlighting the features of equipment of industrial significance so far developed and tested, giving to know three case studies: the Stonehenge case, viability of cutting through waterjet in underground granite quarries and the use of waterjet in quarries. A comparison between the diverse types of technologies is analysed economically and the state of Portugal face to this new technology.

Keywords: Rock cutting, Water-Jet, High pressure, Porosity, Mining Industry, Quarrying

1 – INTRODUCTION

Under the pressure of international competition, dimensional stone industry is now at the edge of a technological revolution implying the introduction of advanced cutting methods, the use of powerful material-handling equipment and the application of better management tools, resulting in a possible spectacular increase of productive parameters, accompanied by a substantial improvement of the material quality.

To this process of modernisation a considerable contribution can be provided by the application of high-velocity waterjet.

Although not much widespread in Portugal, water jet systems became important in many functions of the world’s industries. Some companies have adopted this new method for cutting plates in a precise and detailed manner. Even so, in the mining industry, its application is scarce, if not inexisten. Considering the alternative, the traditional cut methods, the study of water jet and its advantages became a necessity.

Parameters such as process efficiency, equipment dimension, produced racket or cut precision are relevant elements, such as the versatility and energetic efficiency in cutting and cleaning.

Therefore efforts are being made for the improvement of the basic knowledge and the development of suitable commercial equipment meeting the requirements of future quarrying operations.

This article was based on scientific, industrial and technological knowledge acquired by researching and analysing cutting waterjet systems, not forgetting its application in national quarries.

Industry practical necessities, technological and technical knowhow reached through scientific research is one of the objectives of this work.
There are four main sections in a high-pressured water jet system (Figure 1) being:

- Pump
- Control system
- Head
- Energy supplier

With another if mixture is required (case of abrasive jet, for instance):

- Additives compound

The system can be either static or mobile depending on the final objective. In the static system the entire or partial group of sections is movable in less precise cuts requiring better adequate safety rules. Evidently the weight that has to be moved in a mobile system is far greater than static but the pressure loss in the system is also lesser (most of pressure losses occur in tubing, valves, joints e changes of direction; if the system is kept simple or compact what it loses in mobility, gains in jet strength).

2.1 – PUMP

The hydraulic pump is the water provider for the water jet system. It is usually chosen considering the necessary pressure to perform some function. There are many types of pumps and some are more efficient, but expensive while others are simpler but inexpensive. Since the water discharge required is usually between 10 to 60 litters (rarely more) with a possibility for reutilization, most pumps used are single phased or double phased due to an easy maintenance and high liability. Pumps work with pistons, as so provide pressured water in an altered manner (not in a continuous regime). Intensifier process may rectify or at least minimize the effect of such phenomena. This method requires a double phased pump in which the first is used for water compression and the second as a regular pump being feed with a higher pressure.

2.2 – HEAD

The head is the section of the system responsible for giving direction to the water jet. Using control systems (with CAD applications) on a static system with a robotized head is, today, the major use given to these systems for cutting thin plates. The head is composed by a few parts of which the nozzle, responsible for minimizing atomization, and lance, giving more length of influence to the head, are
specially referred. Figure 2 shows an illustration of a head.

![Figure 2 - Illustration of a head with abrasive insertion.](image)

**2.3 – NOZZLE**

Nozzle is a mechanical part specially made for improving water jet direction and convergence. Its simplicity can, generally, be categorized by diameter and aperture angle (Figure 3).

![Figure 3 - Illustration of a nozzle.](image)

It has been extensively studied by researchers such as Rouse, Nikonov, and Leach & Walker that concluded that the best available considering manufacture costs and optimal jet stand-off distance is with an aperture angle of 13º and exit of 4 diameter (exit diameter being ¼ of tubing).

**2.4 – LANCE**

The lance allows an increase of length of the head. If a breach is too thin for the head to enter (recurrent situation in quarrying), the lance is attached. It is composed by a moving mechanism for jet progression and a tube of significant size. Figure 4 shows an example of spear for jet extension.

![Figure 4 - Illustration of a lance.](image)

Since there’s a minimum size for even the spear to enter the breach a single fixed jet will not do the work and it becomes necessary the use of multi-jet, oscillatory or rotating nozzle.

**2.5 – SECONDARY PARTS**

Water jet system is a complex one with many other, non fundamental, parts like the security system, discharge valve and sound container. The sound container prevents sound waves from leaving the near-impact area preventing excessive Db values in the vicinities, Figure 5.

![Figure 5 – Sound container prevents sound waves from leaving the near-impact area.](image)
3 – WATER JET TYPES

There are many water jet types but it can ultimately be divided into two large groups: continuum or discrete. In the first case the jet never ceases its discharge so the jet thrust is of constant strength. If discrete the discharge varies between total and none (Figure 6).

Figure 6 - Water jet large groups: continuum (right) and discrete (left).

The jet may be pure (plane water) or a mix. There’s a wide selection of additives for a water jet but for a cutting purpose its specially important to reference abrasive insertion which consists in mixing solid particles to the water flow which eventually will hit the working surface causing fairly more erosion than a pure jet.

Figure 7 – Illustration of abrasive being mixture with water in the mixing chamber (up), exiting the nozzle (center) and hitting the working surface (down).

4 – CASE STUDIES

In these dissertation three cases has been studied. One related with the construction of a Stonehenge model, another about the feasibility study of cutting granite in underground mine, and one last case, about the cutting of granite on a granite quarry.

4.1 – STONEHENGE

The Stonehenge project is a case carried out by David Summers in 1984, on the Missouri University of Science and Technology. The main aim of this project was to demonstrate that the use of waterjet at high pressure could cut faster and easier than traditional methods, leaving a softer and smoother final cut in comparison with classical cutting forms. So, in 1984, the project was finished using 160 tons of stone, recurring to pressures as high as 130 MPa. The cut has achieved velocities of 2.2 m²/h on the cover stones with 5.4 meters long and 1 of depth. On the other side, the cutting rate on the high quality rocks was between 1.1 to 1.4 m²/h.

The waterjet system used had a nozzle with two rotating orifices of 1mm diameter each. The rotation speed was 180 rpm and even after only six years cutting rates achieved 1.5m²/h. To cut the blocks, successive swept were between 6 and 12 mm with 50 mm width. The generator consumed between 15 to 23 litters/h.

UMR Stonehenge was the first major structure created through high-pressure water jets, and thus marked the transition from mechanical to hydraulic excavation. The monument was made by the group now known as High Pressure Waterjet Laboratory of Rock Mechanics, and Explosives Research Centre, at UMR, under the direction of Dr. Summers, supervision by Dr. Marian Mazurkiewicz and with the help of a group of undergraduate students.
4.2 – FEASIBILITY OF WATERJET SLOTTING IN UNDERGROUND GRANITE QUARRIES

In the second case was studied the feasibility of waterjet slotting in underground granite quarries.

The economic benefits from application of the technology through waterjet in underground, as in open sky, depends mainly of the cutting rate. The performance achievable in field is connected with the operating features of the machine, the characteristics of the material and the tensional state of the rock massif. In this case studied has been found that slotting rate is strongly influenced by the value of induced stress component normal to the cut plane along centreline of the advancing front of the slot. As present drill-based methods using explosives and flame-jet cannot be employed in a confined space, while diamond wire needs the support of others technology, due to its inherent limitations; the waterjet method would match the wire saw, playing a role similar to that of rock. Therefore a suitable combination of these two technologies appears to be the most interesting solution for quarrying granite at depth.

Waterjet is a suitable technology for driving deep slots into rocks having a heterogeneous granular fabric, for the production of squared blocks (Summers, 1987) (Vijay, 1988). Equipment performance depends on the rock (Erdmann-Jesnitzer, Louis & Wiedemeier, 1980) and in particular on its compactness, as confirmed by the presence of a straight relationship between specific energy and P-wave velocity (Agus, Bortolussi, Ciccu, Kim & Manca, 1993)

Cutting rate achievable in a given rock depends considerably on the stress at the bottom of the slot, right where the material is disintegrated under the action of the jet. It has been shown that cutting rate decreases with compressive stress perpendicular to the cutting plane and it increases with tensile stress (Bortolussi, Ciccu, Manca & Vargiu, 1996) (Bortolussi, Ciccu, Grossa & Manca, 1977).

Moreover, experimental evidence suggests that jet pressure should be increased when crossing a strongly compressed rock for winning the tough-to-cut material, whereas hydraulic energy is better exploited using a lower pressure, higher flow rate jet when crossing tensile areas (Bortolussi, Ciccu, Grossa & Manca, 1977)

The much summarized outcome from the curves of Figure 8, show that:

- With the respect of the performance achievable on unstressed samples, slotting rate diminishes gradually as comparative stress grows up, whereas it increases when the rock is subjected to a tensile stress (positive values);
- The effect of pumping pressure is very important since slotting rate eventually approaches that for the unstressed rate sample as pressure is increased from 100 to 200 MPa with the same nozzle diameter (0,96mm);
- The energy consumption increases with the stress, although with different gradients for the different pressures
- In strongly compressed rocks the use of high pressures is greatly advantageous whereas in the case of unloaded rocks specific energy seems independent of pressure, meaning that slotting rate is almost proportional to jet power (in agreement with other laboratory results).
Since cost per unit of area, for a given energy consumption, is inversely proportional to slotting rate, it ensures that attempts aimed at speeding up the operation by adopting every suitable measures and in particular by controlling the stress generated in the neighbours of the slot bottom are of great importance (Ciccu & Bortolussi, 1998).

This is especially true for underground stone quarries, when the tunnel must be opened. In the implementation of cuts must be followed an order, and open slots must be opened in a rectangular area, where it will subsequently be passed to the diamond wire in order to separate the solid block (Figure 9).

![Figure 9](image)

**Figure 9**—Water jet cuts to 3m depth (left) and diamond wire cut on the back of the block with 1.5m (right)

Based in available information, the study of the vertical compressive stress shows that, on the bottom of the slot, it augments with the increase of the cutting area, diminishing with the cutting profundity (distance from the face), as can be seen in the figure 10.

![Figure 10](image)

**Figure 10**—Stress component along the front of a horizontal slot.

In the Figure 10 can also be seen the value of stress component along the slotting direction for a cut area with 6 m long and 3 m deep, under the hypothesis that horizontal and vertical components of original stress is 10 MPa (k=1). It appears that horizontal tension at the slot bottom is roughly 3.5 times the original value after reaching a slotting advance of about 0.5 m from the origin (start drill hole), while it becomes 7 times greater after 3 m. This implies that cutting rate with waterjet is expected to diminish gradually. With the aim of increasing the cutting velocity, the strong vertical tension that is felt at the slot bottom of the cut can be relieved with the application of flat jacks as closest as possible of the transversal water jet (as can be seen in the Figure 10).

Commercially available jacks suitable for this purpose have an edge length of 0.5 to 1 m and are 4 to 5 cm thick when unloaded. The expansion can be 2 to 5 cm.

![Figure 11](image)

**Figure 11**—Schematic drawing of the waterjet lance and the flat jack

Thanks to its geometric features the jack can be placed inside the slot which is typically 5 – 6 cm wide and it can be easily moved when discharged, in upwards direction, in case of vertical slots, or sideways, in case of horizontal slots. This jack can be supported by an iron arm that connects to the lance, so they can be moved together in each cycle. Once that tension decreases when the profundity increases (Figure 10), the move would be made when the nozzle achieves maximum point inside of rock, where consequently the jack would be deflated shortly before and expanded again soon after beginning of the back travel.

Following these principles, studies have been made with computer simulations that shown the induced stress in a section near to the face where the jack is placed are shown in Figure 11 in the assumption that original components of principal stress are
10 or 5 MPa, respectively. Can be seen that the compressive stress at the slot bottom progressively increases with the slotted area, except for the first 2.5 m in the case of original stress of 5 MPa owing to the rigidity of the rock. With the progress of slotting the stress relief due to the presence of the jack tends to correspond to the applied load (around 10 MPa). One tensile stress at the slot bottom is only found during the first 3.5 m of slot length, however increasing the oil pressure to the jack can extend the tensile region.

![Graph 1](image1)

**Figure 12** – Induced stress, normal to the cut plane as a function of the slot length with and without the application of the flat jack. Original stress: 10 MPa (top); 5 MPa (bottom)

The effect of the flat jack is also put into evidence in terms of slotting rate by the curves of **Figure 13**, confirming that the best advantages are achieved in the intermediate range of pressure.

![Graph 2](image2)

**Figure 13** – Slotting rate as function of slot length.

On the time that the experience was made, the more promiscuous aspects of this water jet application would be:

- Bench opening slot (replacing jet flame) and horizontal underhand cut (replacing explosive splitting) in the case of surface quarrying according to the conventional high-bench method;
- As an alternative, L-shaped horizontal and vertical slots, up to 3.5 m deep, on the side face of the bench, (diamond wire can then be encompassed along the exposed perimeter, with no need for preliminary drilling, for the subsequent slicing operation);
- All face cuts in the case of tunnel excavation;
- Perimeters slice delimitation in the case of development of large underground chambers according to the high bench method.

The association of waterjet with diamond wire offers a very interesting solution for mechanised quarrying, since both are able to work in a completely automated fashion.

The importance of stressing conditions of the rock must be emphasized. In fact, rock slotting with waterjet is very sensitive to the stress at the slot bottom normal to the cut plane. A flat jack can be placed into the slot in progress in order to relieve the compressive stress, which would produce a progressive deterioration in slotting rate. However the beneficial effect of stress relief becomes insignificant in what concerns of the waterjet generated at relatively high pressure (200 MPa), at least for the rock tested.

### 4.3 – WATERJET IN DIMENSIONAL STONE QUARRYING

In this third and last case studied it’s summarised the basic knowledge and the industrial experience concerning the application of high velocity waterjet technology (HVWT). It’s given special attention to the results of field experience highlighting the features of equipment of industrial significance so far developed and tested. Under the pressure of
international competition, dimensional stone industry is now on the edge of a technological revolution implying the introduction of advanced methods, the use of powerful material handling equipment and the application of better management tools. To this process of modernisation a considerable contribution can be provided by the application of high velocity waterjet.

First of all, it’s necessary to explain why there are some discrepancies between the values. The main reason why discrepancies are found among experimental results and field experience lies in the great variability of rock features, even within the same area, according to the genesis of the formation, the pattern of tectonic disturbances, the state of stressing and even the effects of the excavation activity itself. Thus the tensional state of the rock in situ, often underestimated in the prediction of cutting results achievable in the field on the basis of laboratory data, is also of a capital importance. In fact, if a rock element is subjected to compression, more energy is required to remove it, since pores are more impervious to jet penetration and isolated fragments remain attached, due to a stronger embedding. On the contrary, disintegration can be favoured in presence of tensile stresses. This statement has been experimentally demonstrated in laboratory, subjecting test samples under slotting to different loading conditions and correlating the cutting rate achieved to the stress at the bottom of the slot, assessed by computer simulation (Bortolussi, Ciccu, Manca & Vargiu), as shown in Figure 14.

It’s important to refer that the effect of rock stressing can be overcome with the increase of water pressure, but this would also increase the price. Due to this, the solution passes through controlling the state of stress of the rocks nearby the cutting local. From the field experiences was observed that granite has a cutting rate from 0.6 to 2.4 m²/h, depending of the system power. As referred before, the comparison between the data is difficult due to the big influence of the rock’s characteristics. Even so it is clear that cuts between 3 and 8 m depends on the lance length and the specific energy is usually lower in cases where bigger water flows have been used, confirming that there is no advantage in increasing the pressure beyond the initial one, typical of each rock. It was also observed that the use of waterjet in quarry applications has been very rare due to a lack of trust between entrepreneurs, who prefer to rely on traditional technologies they know well, to invest large amount of capital and being afraid of experience problems that cannot solve yet by themselves.

5 – CONCLUSIONS AND FURTHER DEVELOPMENTS

Some conclusions may be made as a result of the present work:

- Water jet technology has its main application in rock exploitation and in the superficial finishing of ornamental rock;
- Its use preserves the rock original properties as color and texture, which are intrinsic to the rock’s crystalline structure (this doesn't happen with other methods like the flame jet), what results in a more valuable product;
- The high pressured water jet can be applied, without productivity reduction, to a very thin rock and particularly fragile materials, which may not be workable through traditional methods, allowing a wider field of applications;
- Increasing the number of used nozzles, it also increases, at the same ratio, a higher cut velocity, hence a higher production, while the necessary investment and working costs increase at a lower
Nevertheless, more research projects should be taken to assure the viability of water jet systems, either in terms of rentabil ity and environmental impact;

Scientific research and development in this techniques could improve the technology and its modernization, changing the way it’s seen in both exploitation and superficial finishing’s industries;

There are opportunities to use this technology in the Portuguese underground mines, which technical-economical viability could be tested in a laboratory scale and validated with in situ tests.

6 – REFERENCES


