Improvement of Waterjet Performance in Granite Slotting by Relief of Compressive Stress

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ABSTRACT

The economic benefit resulting from the application of waterjet technology in underground and surface quarrying of dimensional stone chiefly depends on slotting rate. The performance achievable in the field is connected with the operating features of the machine, the characteristics of the material and the tensional state of the rock massif. In particular, it has been found that slotting rate is strongly influenced by the value of induced stress component normal to the cut plane along the centreline of the advancing front of the slot, which increases from the original value of intact rock to levels even 10 times higher. Slotting rate decreases accordingly. A possible strategy for controlling the process of stress accumulation consists in the application of suitable forces against the slot walls with the aim of inducing a favourable stress pattern in the region where rock disintegration takes place. These forces can be applied by means of flat-jacks. In the paper this approach is described and the effectiveness of the method to reduce the normal component of stress and even to induce a tensile stress is demonstrated through numerical simulation. Then the economic benefit is assessed on the basis of the experimental correlation between stress and cutting rate using a waterjet lance with oscillating nozzle.

KEY WORDS: Waterjet Technology, Stone quarrying, Slotting rate, Induced stress,

FOREWORD

Although the basic mechanism involved in rock disintegration by means of high velocity water jets is not yet thoroughly understood, it is widely recognised that the porosity of the material plays a major role. Therefore it seems reasonable to assume that cutting efficiency of a water jet is likely to be influenced by the conditions affecting this parameter. In particular, rock porosity depends on the stressing state of the rock, which gradually changes as slotting proceeds.

In order to evaluate the effects of this phenomenon on waterjet performance, slotting tests with oscillating nozzle have been carried out on granite samples subjected to a static load. Slots were made either in the direction of the compressive force or perpendicular to it. The stressing state near the jet impingement area for the different loading conditions has been assessed using the 3-D FLAC code. Results for the Rosa Beta granite quarried in Sardinia have been discussed in a paper given at the Geomechanics 96 Conference (Bortolussi et al., 1997).

Then the subject has been further developed in a paper presented at the sixth International Symposium on Mine Planning and Equipment Selection 1997 where suitable strategies aimed at overcoming the negative effects of rock stress have been suggested to the benefit of quarrying enterprises (Bortolussi et al., 1997).

BASIC KNOWLEDGE

Waterjet is a suitable technology for driving deep slots into rocks having an heterogeneous granular fabric, for the production of squared blocks (Summers, 1987; Vijay, 1988). Equipment performance depends on the mineralogical and petrographic characteristics of the rock (Erdman-Jesnitzer et al., 1980) and in particular on its compactness, as confirmed by the presence of a straight relationship between specific energy and P-wave velocity (Agus et al., 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 et al., 1996; Ciccu and Bortolussi, 1998).

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 flowrate jet when crossing tensile areas (Bortolussi et al., 1997).

This very important outcome is summarised by the curves of Figure 1.

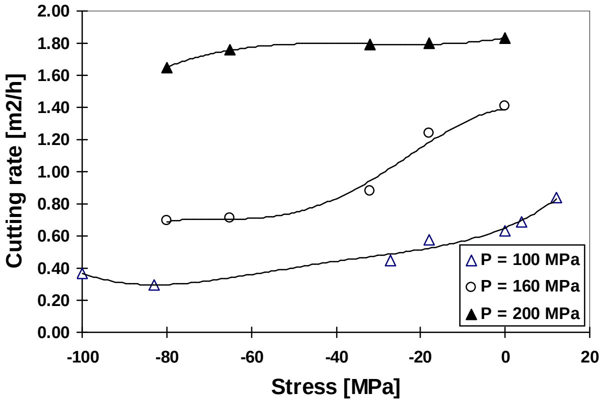


Figure 1. Cutting rate achieved in the Rosa Beta granite as a function of stress at the slot bottom

The curves clearly show that:

- With respect to the performance achievable on unstressed samples, slotting rate diminishes gradually as compressive 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 sample as pressure is increased from 100 to 200 MPa with the same nozzle diameter (0.96 mm);
- at 100 MPa cutting rate is less sensitive to stress since the pressure is close to the threshold value and therefore waterjet performance is poor even under very favourable stress conditions;
- at 200 MPa the curve is almost flat meaning that the pressure is high enough to win even a highly compressed rock;
- the most evident advantage is achieved for intermediate pressures between 100 and 200 MPa;
- energy consumption increases as a function of stress, although with different gradients for the different pressures as indicated in Table 1;
- in the case of 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 findings;
- if tensile stresses are induced, specific energy is smaller at lower pressures and slotting rate can be increased by acting preferably on the water flowrate.

Table 1. Specific energy as a function of normal stress at the slot bottom in granite

STRESS [MPa]	SLOTTING RATE [m^2/h]			SPECIFIC ENERGY [MJ/m^2]		
	100 MPa	160 MPa	200 MPa	100 MPa	160 MPa	200 MPa
- 80	0.30	0.69	1.64	260	231	136
- 60	0.36	0.71	1.78	217	224	125
- 40	0.44	0.84	1.80	177	190	124
- 20	0.52	1.15	1.80	150	139	124
0	0.63	1.39	1.84	124	115	121
+ 10	0.78	1.42	1.88	100	112	119

Since cost per unit area, for a given energy consumption, is inversely proportional to slotting rate, it ensues 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 a great importance (Ciccu and Bortolussi, 1998).

This is especially true for underground stone quarries for the production of squared blocks where the first phase of the excavation method to be carried out is the opening of an entry tunnel from the hillside until reaching the planned quarrying space; at that point the tunnel is further enlarged over the entire area, leaving pillars in place for the sake of roof support.

In the case of thick deposits, excavation can be further developed below the level of the access tunnel inside a large chamber which is progressively emptied by layers taken with a downwards sequence, creating a bench configuration like in daylight operations. However, whereas at this stage the rock to be excavated is no more subjected to stress which is almost thoroughly relieved owing to the presence of new free faces, the effect of compression is very important during the excavation of the access tunnel when only the free face of the advancing front is available, with no lateral access. The fulfilment of this work implies a number of horizontal and vertical slots to be driven from the face into the rock using waterjet and diamond wire (or shearing devices) (Ciccu and Fiamminghi, 1996).

A waterjet equipment used for tunnel excavation in a Japanese granite quarry is shown in figure 2.

Figure 2. Tunnel excavation in a Japanese quarry by means of waterjet slotting equipment.

For each advance step of tunnel excavation a pilot hole is first drilled perpendicular to the face, from which a slot can be started. The waterjet lance, bearing the oscillating nozzle directed towards the rock to be excavated, is traversed forth and back parallel to the pilot hole and after each cycle it is periodically moved sideways by incremental steps, thus extending progressively the rectangular area slotted until reaching the opposite end of the slot (Figure 3). From the first one all subsequent slots can be started following a convenient order.

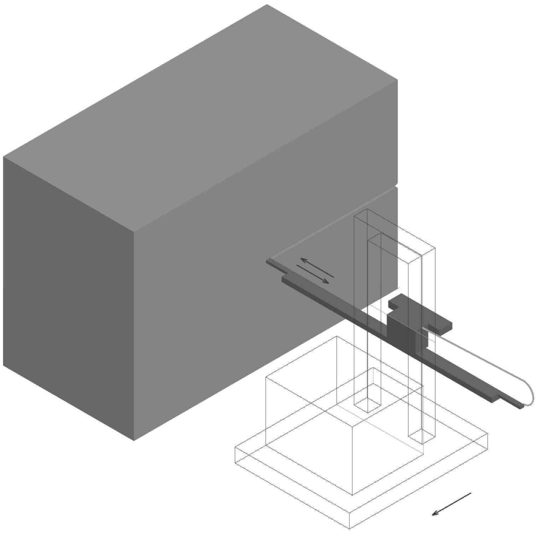


Figure 3. Scheme of tunnel excavation in underground granite quarry using waterjet and diamond wire. First phase: Waterjet slotting at the face. Slot depth: 3m.

Once all the waterjet slots are completed, individual blocks can be extracted by cutting the back hidden face with diamond wire every 1.5 metres, or shearing it with wedges or jacks introduced into the slots (Figure 4).

The first slot is the most critical one regarding stress concentration that builds up progressively with time at the slot bottom.

In the development of the numerical model for the assessment of stress redistribution, the orientation of Cartesian axes adopted was the following:

Y-direction =horizontal parallel to the tunnel face
Z-direction = horizontal perpendicular to the tunnel face
X-direction = vertical parallel to the tunnel face

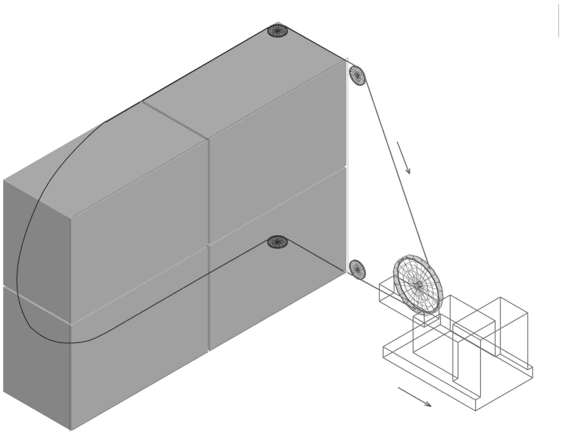


Figure 4. Scheme of tunnel excavation in underground granite quarry using waterjet and diamond wire. Second phase. Diamond wire sawing of the rear face in two stages of slicing. Block width: 1.5 m

Therefore the jet is traversed in the Z-direction and the cross sections of the slot are taken parallel to the X-Y plane.

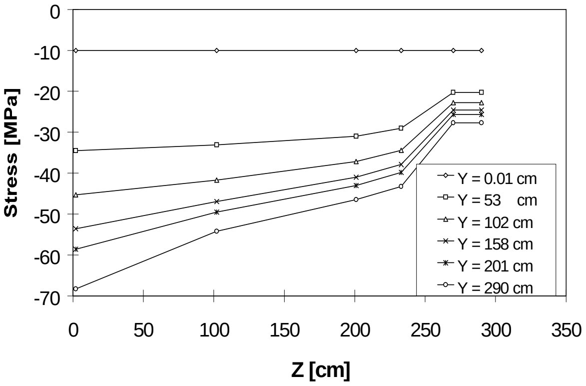
In agreement with the results available in the literature, stress analysis for granite (bulk modulus 5 GPa, shear modulus 2 GPa) has shown that, at the slot bottom, the compressive stress component normal to the slot plane increases with the slotted area. Moreover, it decreases along the Z-direction, i.e. as a function of the distance from the face.

Figure 4 shows the value of stress component σ_{xx} along the slotting direction Y for a cut area 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 σ_{xx} 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 drillhole), while it becomes 7 times greater after 3 m. This implies that cutting rate with waterjet is expected to diminish gradually as the slot proceeds in the Y-direction.

Figure 4. Stress component σ_{xx} along the front of a horizontal slot as slotting proceeds in the Y direction.

Moreover the fact that, for a given value of y, the stress component σ_{xx} decreases in the Z-direction gives the opportunity for a partial recovery of cutting rate by adjusting properly the traverse velocity of the



lance through automatic control device when the nozzle is deeper into the rock .

As further slots are performed, stress is gradually relieved from the initial state until the final condition of practically unstressed rock; cutting rate achievable with waterjet varies accordingly.

Therefore the accurate study of the evolution of stress determined by the addition of new slots is of a great importance.

Since waterjet efficiency considerably decreases in presence of compressive stress, suitable cutting sequences should be devised in order to generate a stress pattern characterised by minimum compression or even traction in the slotting region.

Equipment performance and thence cutting cost can be optimised by adopting suitable measures on the basis of the actual stress encountered during the operation, taking into account the practical limitations of the machine and the restrictions related to the narrow space available underground. In particular the following aspects are worth underlining:

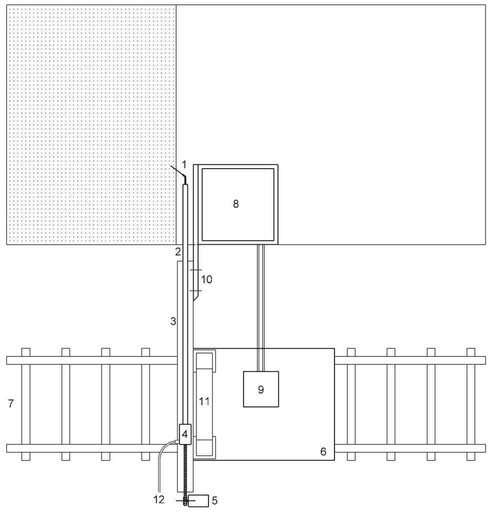
- The shape and size of the tunnel should be selected in such a way that the area of stress-favoured slots is increased;
- for the same purpose the blocks should be positioned inside the available space in the most profitable way;
- idle time should be minimised taking into account the features of the equipment;
- traverse velocity of the lance should be adjusted in real time as a function of the variable stress encountered at the slot bottom across the slotting plane.

Besides these measures, the possibility of relieving the state of compression or even of inducing a tensile stress by applying an artificial support acting against the slot walls can be taken into consideration.

PROPOSED SOLUTION

In order to increase the slotting rate, the strong compressive stress perpendicular to the cut plane that builds up at the bottom of the slot can be relieved by placing a flat jack as close as possible to the traversing jet.

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.



1. Waterjet nozzle
2. Traversing lance
3. Driving boom
4. Oscillation motor
5. Traverse motor
6. Moving platform
7. Rails
8. Flat jack
9. Hydraulic pump
10. Connecting arm
11. Main frame
12. High pressure hose

Figure 5. Schematic drawing of the waterjet lance and the flat jack

They can be pressurised with oil up to a level of 10 - 15 MPa providing a total force of 100 - 150 kN against the walls of the slot over an active surface of 1 m^2. The time needed to discharge the jack and to load it again is rather short, of the order of few seconds using a pump with a flowrate of 2 l/s, owing to the small inner volume (less than 20 litres for a 2 cm expansion).

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 the case of vertical slots or sideways in the case of horizontal slots.

Practically the jack can be supported by a steel arm rigidly connected to the lance-driving structure so that it is moved together with the lance by elementary steps at the end of each cycle, enabling to maintain its distance from the slot front constant.

Since the stress at the far end of the slot is relatively low (see the curves of Figure 1) the step forward can be imparted when the nozzle reaches the dead point inside the rock and therefore the jack should be deflated shortly before and expanded again soon after the beginning of the back travel. The top view of the slot surface showing the position of the waterjet lance and the flat jack is given in Figure 5.

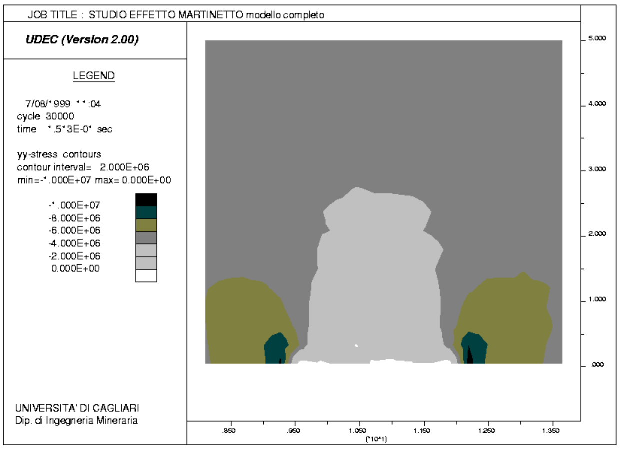
The effectiveness of this solution has been studied by computer simulation as discussed in the following paragraph.

COMPUTER SIMULATION

From the results of the 3D numerical simulation of stress redistribution during a slotting operation (see the curves of Figure 4), it ensues that the idea of using a flat jack can provide a better advantage if the jack itself is placed as close as possible to the slotting front near the tunnel face, where compressive stress is higher, and it is moved by steps in the Y direction as slotting proceeds.

This allows to study the problem in a X-Y plane orthogonal to the slot area using the 2D UDEC code for numerical simulation, with minor loss of significance in the results.

For the numerical simulation a study volume 18 m high (in the X direction) and 12 m wide (in the Y direction) has been considered while the length in the Z direction has been assumed to be infinite.

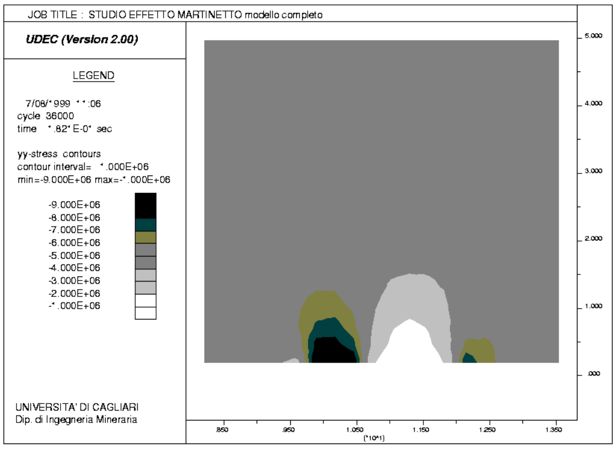


Inside this volume a horizontal slot 6 m long is made starting from the lower right corner of the solid. The specular features of the problem with respect to the slot plane enables to carry out the analysis on the upper half of the study volume introducing suitable constraints in the symmetry plane.

The solid has been divided into a pattern of discrete elements the size of which increases farther from the slot area towards the periphery. The lower border is constrained in the Y direction whereas the left vertical edge is constrained in the X direction (no displacement allowed). On the two remaining edges the forces deriving from the assumption of an original stress with horizontal and vertical components of principal tensions both equal to 5 or 10 MPa (k = 1) have been applied.

The characteristics of the constituent material (granite rock) assumed for the model are the following:

- Material behaviour: Linear elastic
- Volumic mass 2,600 kg/m^3
- Young modulus: 7.5 GPa
- Poisson coefficient: 0.25



a)

a) b)

Figure 6. Distribution of induced stress after 3.5 m of slot. Original stress: 5 MPa
a) without the jack, b) after the application of the jack for stress relief

The analysis has been carried out for the first horizontal slot of the sequence which is the most critical one.

In order to highlight the advantage achievable with the concept of stress relief, the slotting operation has been simulated before and after the application of the flat jack as described earlier.

The stress situation for the two conditions of original stress has been studied after the first 1.5 m of slot (necessary for placing the jack) and then every 1 m until covering the slot length of 6 m. Oil pressure to the jack was assumed to be 10 MPa.

RESULTS AND DISCUSSION

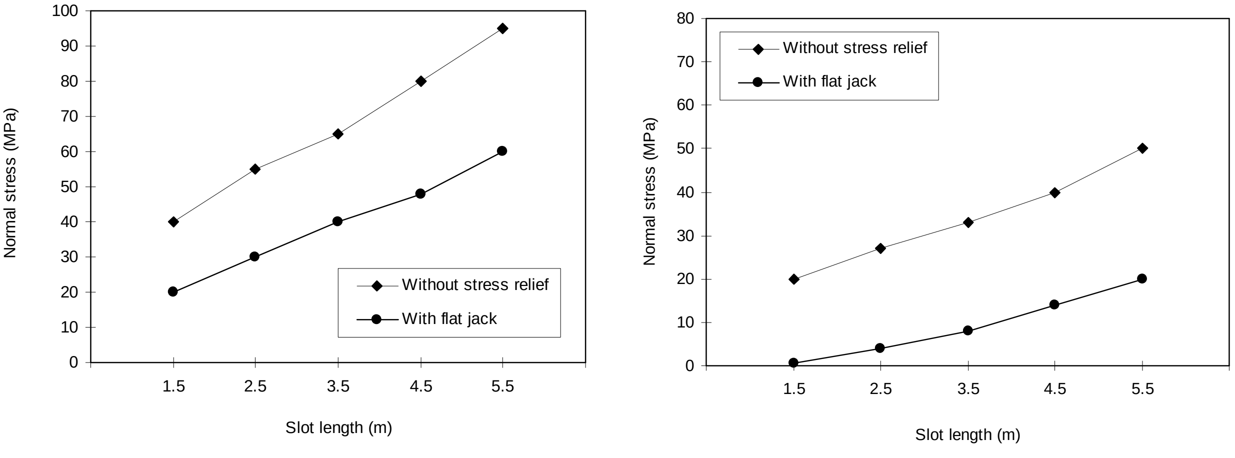
Technical aspects

The typical distribution of induced stress in a vertical section through the jack is shown in Figure 6.

The curves showing the value of induced stress in a section close to the face where the jack is placed are shown in Figures 7 a) and b) in the assumption that original components of principal stress are 10 or 5 MPa, respectively. The curves show that:

- 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).

- a tensile stress at the slot bottom is only found during the first 3.5 m of slot length. The tensile region can be extended by increasing the oil pressure to the jack.



a) b)

Figure 7. Induced stress σ_{xx} normal to the cut plane as a function of the slot length with and without the application of the flat jack. Original stress: a): 10 MPa; b): 5 MPa.

The effect of the flat jack is also put into evidence in terms of slotting rate by the curves of Figure 8 confirming that the best advantages are achieved in the intermediate range of pressure.

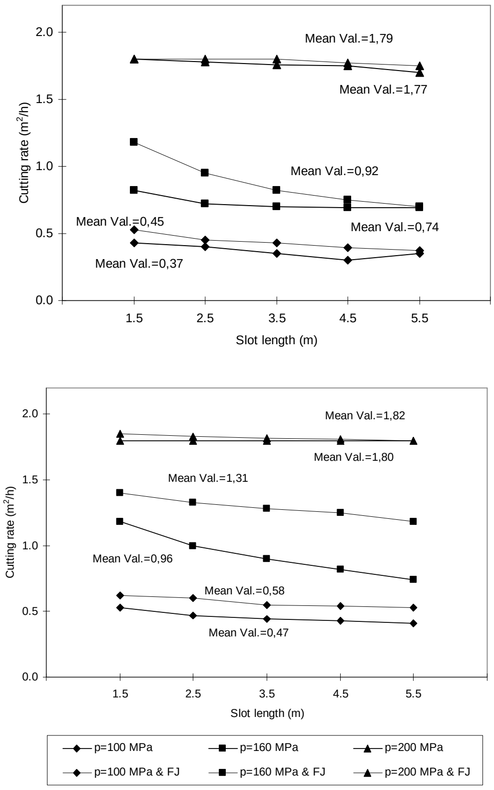


Figure 8. Slotting rate as a function of slot length

Economic significance

In waterjet slotting the typical hourly cost [US$/h] incurred in the quarry can be calculated through the expression:

$$C = (C_eP/R + C_m + C_r + C_p + C_d)$$

where:

- P	Total power (hydraulic and mechanical) [kW]
- R	Transformation efficiency = 0.7

assuming that:

- C_e	Unit cost of energy [US$/kWh] = 0.095
- C_m	Cost of manpower [US$/h] = 12.5 (one worker attending)
- C_r	Cost of consumables (nozzle) [US$/h]: 2.2
- C_p	Cost incidence of spare parts (pistons, electric components, hose etc.)
- Cd	Equipment depreciation

The Unit cost of cutting U [US$/m^2] is given by:

$$U = C/ V_m \qquad (1)$$

where V_m is the average slotting rate [m^2/h]

Calculations according to the above approach gives the results summarised in the following Table 2.

Of course the hourly cost of slotting increases with pressure due to the increase in energy and water consumption, a higher nozzle wear and a more frequent replacement of the HP hose and of spare parts of the pump.

Table 2. Hourly cost in waterjet slotting (0.96 mm nozzle)

PRESS.	H. POWER	HOURLY COST [%]	TOTAL

[MPa]	[kW]	Energy	Water	Nozzles	Labour	Spare parts	Depreciation	[US$/h]
100	22	19.0	2.9	3.7	23.7	27.5	18.5	72.85
160	44	26.5	3.2	3.8	20.4	23.8	17.5	84.67
200	62	30.8	3.2	4.3	18.2	21.3	17.7	95.06

Table 3. Slotting cost [US$/m^2] (0.96 mm nozzle)

PRESSURE [MPa]	SLOTTING COST [US$/m^2]			
	Original stress: 5 MPa		Original stress: 10 MPa	
	Without flat jack	With flat jack	Without flat jack	With flat jack
100	155.0	127.8 (-18 %)	197.0	161.8 (-18 %)
160	87.3	64.6 (-26 %)	114.4	92.0 (-20 %)
200	52.8	52.5 (- 1%)	53.7	53.1 (- 1%)

Depreciation is also a bit higher being the pump more expensive.
The unit cost of slotting calculated according to (1) is shown in Table 3.
Cost figures show that:

- The application of a flat jack aiming at relieving the compressive stress induced at the slot bottom entails a considerable reduction in slotting cost per unit area by about 20 - 25 %, except for the case when high pressures are used;
- cost saving would have been higher not considering depreciation;
- it seems that going up with the pressure would always be advantageous on economic grounds, although it would be interesting to compare the situation at equal hydraulic power.

CONCLUSIONS

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.

The advantage is also achieved on economic grounds since no additional cost would be incurred except for the cost of the jack and auxiliaries, negligible with respect to the other cost items.

However the beneficial effect of stress relief becomes insignificant in the case of the waterjet generated at relatively high pressure (200 MPa), at least for the rock tested.

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