EFFECT OF THE STRESS STATE ON WATERJET PERFORMANCE IN ROCK SLOTTING

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ABSTRACT The economic benefit resulting from the application of waterjet technology in underground and surface quarrying of dimension 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 order to assess the influence of the state of stress of the massif on the slotting rate, tests with oscillating nozzle have been carried out on samples subjected to a static load, either in the direction of the compressive force or perpendicular to it. Results are illustrated and discussed and conclusions are drawn regarding the effect of the tensional state of the rock on material removal rate.

1 FOREWORD

Surface quarrying is the most widespread method for extracting dimension stones. This is mainly due to the relatively low depth of the deposits and to the difficulties in the application of traditional technologies in an underground environment. On the other side, in developed countries, new constraints are continuously imposed to surface activities by the environmental legislation. The solutions aimed at mitigating the impact on the environment during the production activity and the land reclamation required at the end of the quarrying, introduce negative issues in the overall economic balance of the industrial enterprise. Considering that quarrying consumes land surface, landscape, and, clearly, the natural resource, it must be conducted with the maximum achievable efficiency. It means that efforts have to be directed to minimize the negative effects on the environment and to improve the recovery of the geologic resource (Agus et al. 1997).

To these concerns underground quarrying appear to be better suited to the modern trend. In fact it minimizes the consumption of land, reduces the impact on the landscape and requires few and cheap interventions for the final land reclamation.

Underground quarrying is widely diffused in the marble extraction industry (Fornaro et al. 1992) while it is rarely adopted for granite extraction. This fact is mainly due to the cutting technologies used in the two cases: the diamond wire and the rock-cutter for marble extraction, drilling and explosive splitting for granite. While marble cutting technologies are suited for an underground environment and have been adopted with few modifications, those for granite can hardly be used underground. In the last decades two technologies have been developed that can make feasible granite underground quarrying: diamond wire and waterjet slotting.

Diamond wire needs the support of another technology, due to its inherent limitations. To this end, waterjet would match very well the wire saw, playing a role similar to that of rock-cutter in marble quarries.

Therefore a suitable combination of these two technologies appears to be the most interesting solution for quarrying.

2 UNDERGROUND QUARRYING

The underground granite quarrying method here proposed makes use of a combination of diamond wire and waterjet technologies.

A waterjet equipment used for tunnel excavation in a Japanese granite quarry is shown in Figure 1.

Figure 1. Tunnel excavation in a Japanese quarry by means of waterjet slotting equipment

The access underground would consist of a large gateway tunnel, from which production activity can be developed. 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 2). From the first one all subsequent slots can be started following a convenient order.

Once all the waterjet slots are completed, individual blocks can be extracted by cutting the back hidden face with diamond wire (Figure 3).

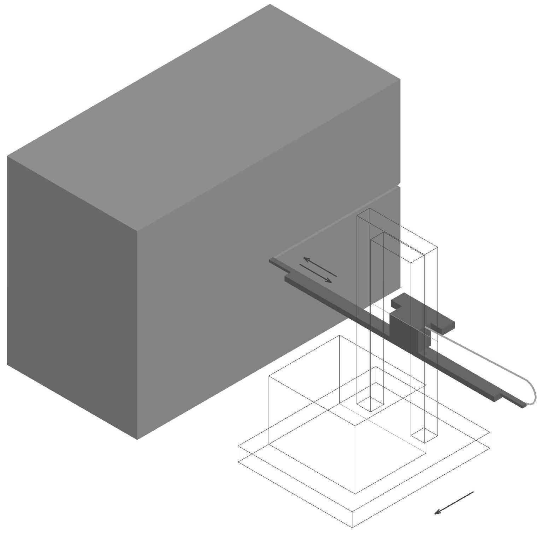

Figure 2. Scheme of tunnel excavation in underground granite quarry using waterjet and diamond wire. First phase: Waterjet slotting at the face. Slot depth: 3m

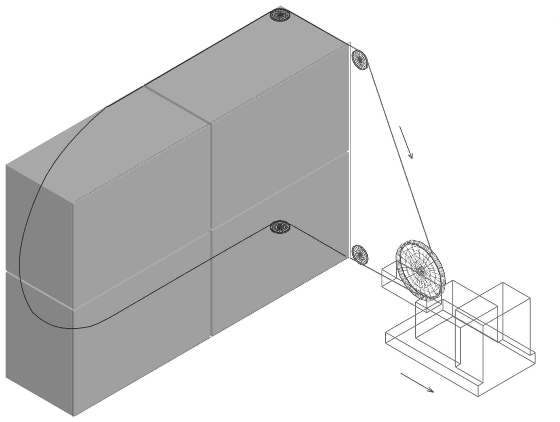

Figure 3. Scheme of tunnel excavation in underground granite quarry using waterjet and diamond wire. Second phase. Diamond wire sawing of the rear face in two stages of slicing. Block width: 1.5 m

In the case of flat orebodies, blocks will be extracted by room-and-pillar method according to a well planned layout, whereas in the case of steeply dipping formations rock will be excavated by levels that are worked out individually with a downwards sequence, leaving large chambers some tens of meters high.

Regarding bench geometry, two configurations can be adopted:

A - High bench, where the vertical extent of the face varies from 6 to 18 m, according to cases. Commercial blocks, whose size ranges from 4 to 12 m^3, are produced with a sequence of cascade subdivisions. A primary block, up to 2,000 m^3 in size, is first isolated from the hillside and then split into secondary blocks (slices), about 100 - 200 m^3 big and 1.5 to 3 m wide, that in turn are toppled to the floor. Production of final blocks takes place by means of suitably directed cuts across the thickness of each slice, aimed at separating the valuable stone from the defective material to be dumped as a quarry waste. This variant is applied whenever a selection is needed. Quarry recovery typically varies from 20 to 60%.

B - Low bench, where face height is smaller than 3 m. Commercial blocks are individually extracted right from the bench, their size being of the order of 10 m^3 with a very narrow range of variability. Recovery can be considerably large. This variant should be preferred if selection is not needed (rock exempt from flaws and little fractured).

3 INFLUENCE OF THE STRESS ON THE WATERJET PERFORMANCE

Many industrial experiences demonstrate that the slotting rate achievable on a given rock, with fixed operational parameters (waterjet pressure and nozzle diameter, lance traverse velocity, nozzle oscillation frequency) depends on the state of stress acting in the rock mass being cut (Ciccu 1993, Ciccu and Flamminghi 1996).

Aimed at finding the relation between the rock's state of stress and the slotting rate an experimental research has been started at the DICAAR waterjet laboratory.

3.1 Experimental set-up

The experimental set-up consisted of:

- a Hammelmann High Pressure plunger pump (power at the engine flywheel: about 300 kW; maximum flowrate: 54 l/min at 250 MPa);
- a waterjet lance provided with an oscillating nozzle (top frequency: 20 Hz; maximum traverse velocity: 15 m/min);
- a block carrier platform (minimum advance step: 1 mm/cycle);
- a programmable control unit;
- a specially designed uniaxial compression cell provided with a hydraulic jack capable of imparting a load of up to 100 t to the sample.

Tests have been carried out under the following experimental conditions:

- pressure: 100, 160 and 200 MPa
- nozzle diameter: 0.96 mm
- oscillation frequency: 20 Hz
- sweeping angle: 22° on each side
- advance per stroke [mm] and traverse speed [m/min]: variable

3.2 *Material*

Cubic samples of a granite quarried in Sardinia, whose main characteristics are given in Table 1, have being used.

Table 1. Physical and mechanical properties of the Rosa Beta granite

Properties	Meas. Value
Bulk specific gravity [kg/m^3]	2,588
Absorption coefficient [%]	4.85
Porosity [%]	0.63
Compressive strength [MPa]	1,920
Flexural strength	156
Impact test (Height of fall) [cm]	68
P-wave velocity [m/s]	5,626

3.3 Testing procedure

Four series of tests have been carried out with variable setting of pressure and traverse velocity, at constant nozzle diameter, oscillation frequency and sweeping angle.

Each series was conceived for putting into evidence the effect of stressing in relation to the cutting direction. The first series was aimed at disclosing the variation of volume removal due to a compressive load applied in the central part (shadowed area) of a parallelepiped shaped sample, perpendicular to the cutting plane, as shown in Figure 4.

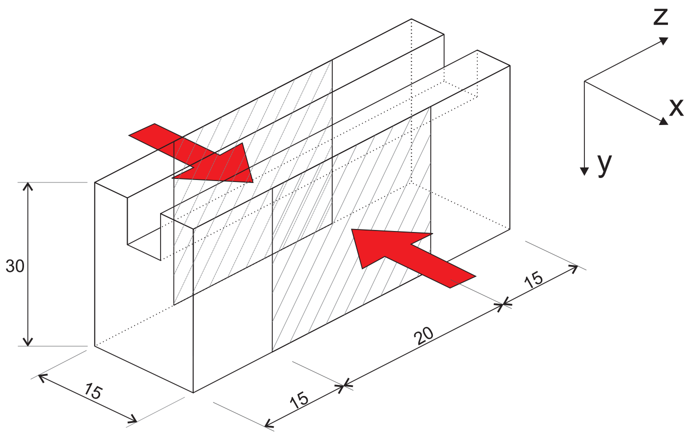

Figure 4. Experimental conditions for the first series of test

Three tests have been made at variable jet pressure (200, 160 and 100 MPa), under a load of 50 t.

Since the effect of stressing is enhanced near the pressure threshold of the rock, the further three series of tests have all been carried out at 100 MPa. It was also decided to maintain the advance per cycle constant (2 mm) and to find the peak cutting rate by varying the traverse velocity.

The purpose of the second series was to put into evidence the effect of a static load parallel to the cutting plane, as shown in Figure 5.

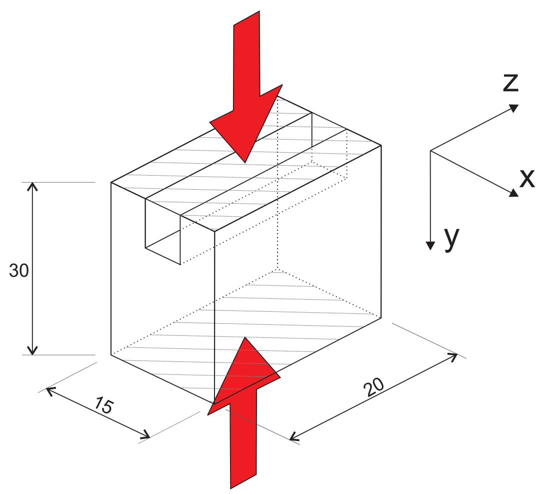

Figure 5. Experimental conditions for the second series of test

The slot was made nearer to one of the free faces of the sample in order to show the effect of load unbalance, producing a differential stress at the slot sides.

The necessary clearance for the traversing lance was obtained by opening a 6 cm deep slot before imparting the load. The variation in cutting rate with depth of slot was then determined.

The third series of tests was carried out subjecting the sample to an evenly distributed lateral compression (25 and 50 t): the effect of stress on cutting performance was assessed by measuring the maximum slot depth down to which predetermined levels of cutting rate could be maintained.

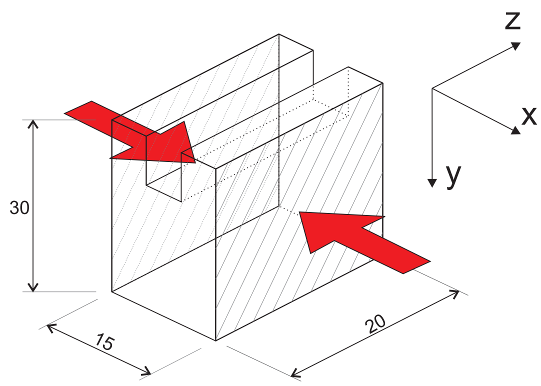

Figure 6. Experimental conditions for the third series of test

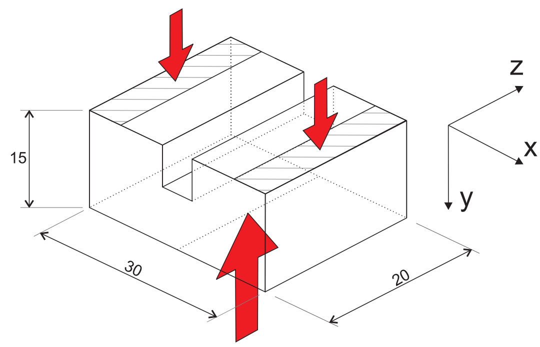

Figure 7. Experimental conditions for the fourth series of test

Loading conditions are shown in Figure 6. Finally, the alleged favorable effect of tensile stress on cutting rate was investigated by applying a flexural load as illustrated in Figure 7.

Stress distribution in the neighbors of the slot bottom was assessed using the three-dimensional FLAC code. The study was carried out on suitable cross sections of the cubic samples used for the experiments, at variable slot depth.

Samples have been spatially oriented as follows:

Z-direction = axis of the slot

Y-direction = depth of the slot

X-direction = perpendicular to the slot plane

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

3.4 Results

3.4.1 Preliminary investigation

Results obtained with the first series of tests are summarized by the curves of Figure 8 giving the relative variation in volume removal per unit length of slot for the different cross sections of the sample.

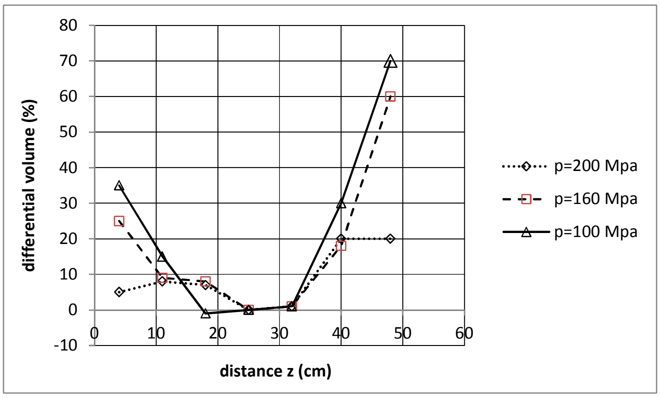

Figure 8. Variation in volume removal along the Z-direction

From the comparison of these curves it clearly appears that:

- volume removal is considerably lower in the central part of the sample where compression is higher;

- average slotting velocity at 100 MPa resulted to be 0.45 m^2/h, lower than that obtained in the case of unloaded samples (0.63 m^2/h); this performance is approached at both extremes of the sample where stress is gradually reduced;

- the variation in volume removal is much more evident in the case of 100 MPa pumping pressure, as expected.

3.4.2 Compression parallel to cutting plane

Under a constant load of 25 t, it was found that cutting rate decreased to 0.48 m^2/h after deepening the initial slot by further 10 cm and to 0.39 m^2/h after additional 15 cm, compared to 0.63 m^2/h achieved on the unloaded reference sample.

It was also observed that slot walls were very smooth and that the bottom showed an unusual section characterized by a marked excavation at the corner corresponding to the thicker leg between the slot and the lateral free face of the sample.

3.4.3 Compression perpendicular to cutting plane

Results confirm the indication of the first series of tests, as shown in Table 3 giving the maximum slot depth achievable with predetermined levels of cutting rate as a function of compressive load.

Table 3. Depth of slot as a function of compressive load at different cutting rates.

Load [t]	Cutt. rate [m^2/h]	Depth [mm]	
		Marg.	Abs.
25	0.45	25	25
	0.36	10	35
	0.30	>25	>60
50	0.45	15	15
	0.36	10	25
	0.30	25	60

It is clear that, as the slot is deepened, the resisting area is progressively reduced, entailing a corresponding increase in compressive stress. This explains the decrease in cutting rate at depth.

Moreover, the higher the external load, the shallower the slot that can be excavated with a given cutting rate, roughly with a reverse-proportion trend.

The negative influence of compressive stress on jet performance appears demonstrated.

3.4.4 Flexural load

By applying a force of 5 t at the central line between two flat 5 cm wide bearings, cutting rate increased from 0.63 to 0.69 m^2/h over 34 mm depth. On doubling that force, cutting rate jumped to 0.84 m^2/h over further 30 mm, then the sample split apart.

The explanation of this outcome is trivial: jet performance is greatly enhanced if the rock at the bottom of the slot is subjected to tensile stress, whereby preexisting and newly induced cracks are better propagated, producing a faster rock disintegration (Erdman – Jesnitzer 1980).

Cutting rate appears to be very well correlated with σ_x as shown in Figure 9 where the results of all tests are reported.

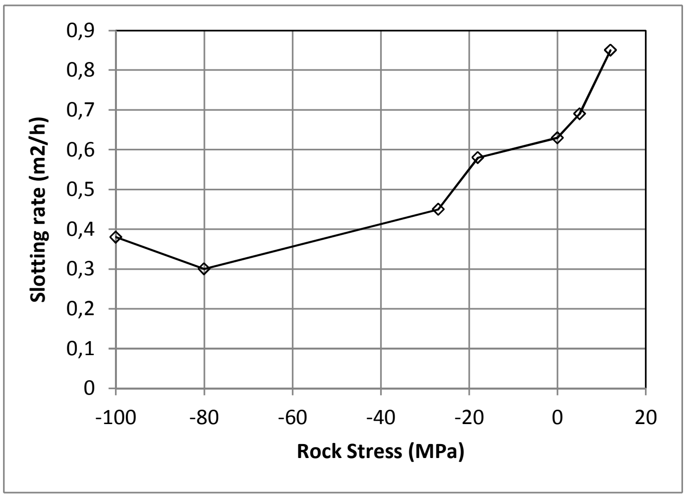

Figure 9. Cutting rate versus maximum σ_x stress component at the central point of the slot bottom

4 CONCLUSIONS

At the present state of the art, the most promising prospects concerning the application of waterjet in granite quarries are for:

- bench opening slot (replacing flamejet) 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 (no substitute technologies are at hand) in the case of tunnel excavation;
- perimetrical 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 mechanized 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.

The considerable influence of stressing state on waterjet performance in rock slotting with high velocity waterjet have been demonstrated by the results of the described experimental research.

In particular cutting rate increases if the rock near the slot bottom is subjected to tensile stress whereas it deteriorates in presence of compressive stress.

Therefore in quarrying operations suitable cutting sequences should be devised in order to generate a stress pattern characterized by prevailing traction in the slotting region.

When crossing a strongly compressed rock, jet pressure should be increased 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 (Summer 1987, Agus et al. 1991, Agus et al. 1993).

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