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Technological and Economic Evolution of Diamond Wire Use in Granite or Similar Stone Quarries

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ABSTRACT: Cutting with diamond wire saws in hard stones, such as granites, gneisses, syenites and diorites, taken together with the dynamic splittmg system, using a detonating cord, has become more widespread because of the operating versatility of the cutting machinery and because of the good productive results. It is obvious that there is an advantage in marketing blocks which have finished-off faces, with no wastes in the squaring phase, especially when high-value dimensional stones are concerned. The excavation of channels within the good rock and the realization of artificial "easy ways" (splitting surfaces) could economically justify the higher cost of diamond wire technology in comparison with explosive splitting. The present paper, according to recent surveys carried out in many stone quarries in Piedmont and Sardinia, supplies new data in order to make a technical-economic comparison between different quarrying systems.

1 INTRODUCTION

The wide and heterogeneous family of dimension stones has in common the fact that they must be obtained in the form of commercial blocks, which means sound blocks of parallelepiped shape usually weighing 5 to 15 t, suitable for further processing and for the production of slabs or other architectural items.

The mining stage of the dimension stone industry conforms to one of the two general strategies quoted below:

A. large volumes of rock, usually in the range of thousands of m^3, are removed by primary cuts from the rock body and, subsequently, stepwise, divided into commercial blocks; unsuitable material is discarded at this stage;
B. commercial blocks are directly cut from the rock body; this method is mostly applied to very regular and homogeneous deposits and especially to underground operations.

Ample cut or split surfaces have to be produced at a reasonable cost and without impairment of the rock soundness.

2 TECHNIQUES EMPLOYED IN ITALIAN QUARRIES

Italian production of commercial blocks (nearly 5 Mt/y of marbles, more than 1 Mt/y of granites and about 1.5 Mt/y of other stones) is mainly the result of three well-established technologies: diamond wire sawing, chain cutting (for *soft* rocks only) and detonating cord splitting.

In *hard* (granites and similar) dimension stone exploitation, the most economical production system, at least for primary cuts, is still splitting by explosives, which can be considered an extreme application of controlled blasting concepts and precision drilling techniques. Very thin linear charges, represented by strands of detonating cord, are placed in parallel, closely spaced holes, stemmed with a suitable shock-absorbing material like water, and simultaneously detonated by a master cord. Fracture is due to tensile stresses in the rock inter-hole bridges, and excess energy from the blast provides the required small displacement of the separated mass (Mancini et al., 1996a). In well-conducted operations, the half casts of the holes are perfectly observed and no extra cracks occur. Productivity is high and İs dictated by the drilling system (Mancini et al., 1994). Although there have been numerous research studies carried out by a lot of laboratories in order to improve the directional splitting action of explosive charges, the most commonly used technique İs still the conventional, firmly established detonating cord splitting method (an estimated 12000 km of cord is consumed yearly for this application in Italy).

Examples of the application of this method are given İn Figure 1.

Figure 1. Example of a typical hard stone quarry exploited with dynamic splitting method

The other two common methods rely on stone machining by microtools, that is to say, tools acting with a very small depth of the elementary cut. Both belong, in principle, to the continuous saw family: cutting tools are attached to a flexible, continuous support, whose motion is unidirectional. The chain cutting method will not, however, be treated in this context, being employed exclusively for marble and, generally speaking, for *soft* rock extraction.

Diamond wire sawing has been, since the end of the seventies, the most widespread technology for marble cutting: in fact, more than 90% of marble quarries use it systematically in cutting operations.

However, problems related to the abrasive properties of *hard* rocks have made its use with them very difficult. Consequently, only at the beginning of the nineties were there the first convincing, though not regular, applications. Today, in Piedmont extractive basins, at least 30% of *hard* rock quarries use diamond wire in several exploitation steps.

Only *plasticized* or *rubberized* wires are used, but the latter is coming to be preferred in quarrying activities. Beads are always *impregnated* with synthetic diamonds; their diameter is 10-11 mm and there are 35-43 beads per meter of wire.

The main features and performances of the diamond wire sawing method are summarised in Table 1. As the wire is rather expensive (over 100 US$/m, and up to 150 US$/m for special purpose types), it is important to get good performances, which are usually defined by two parameters: productivity (m^2/h) and wire service life (m^2/m). The latter parameter is only loosely defined, because the wire can be reconditioned many times before discarding (up to 5 times, usually 1-2 times for hard rocks); reconditioning is a high-skill, labour-intensive task, entailing wire disassembling, reusable bead selection, discarded bead replacement and wire reassembling. Judgement of what is a reasonable, economically efficient, reconditioning rate depends on local circumstances. Diamond wire is often used to "death" in *hard* stone quarrying operations, that is, until the cutting tools are completely worn out, just because bead life is more or less equal to that of the support.

Table 1 Main features of the diamond wire sawing method

Features of the diamond wire saw	
Tool material	Diamonds
Tools geometry	Random
Depth of trie elementary cut	10 ÷ 30 µm, vairable
Width of the cut	≅ 1 cm
Flushing	Water (≅ 50 l/min)
Tools speed	20 ÷ 40 m/s
Flexible support type	Steel cable
Length	>100 m
Guidance	Pulleys
Beads type	Impregnated (hard rocks)
Beads, number/m	35 ÷ 40
Wire cosi, US$/m	140 ÷ 150
Productivity, m^2/h	1 ÷ 4
Service life, m^2/m	8 ÷ 10 (hard rocks)

3 ECONOMIC COMPARISON OF CUTTING TECHNOLOGIES

Basic conditions for the success of a new technology are its simplicity and cheapness in comparison with other already-used methods. Of course, there are other important aspects which should be considered in the choice of the cutting method: first of all its safety, its flexibility and adaptability according to rock body characteristics (Mancini et al, 1995).

Not only should low production costs be taken into account, but also the method's *recovery;* that is, how much of the quarried stone will be really exploitable in further processing. For instance, a technology with higher costs, but which is more accurate, could turn out to be cheaper when high-value materials are concerned.(Agus et al., 1990)

A schematic comparative analysis of costs connected with primary cutting of a gneiss bench in an Alpine basin is reported here. Quarry-front cutting is the first phase of the production cycle in a dimension stone quarry and it involves an expenditure of energy, machinery and human resources which are variable according to the technology used. The main purpose is always to get a cut without cracks in the bench or in the rock body, m a short time and with low costs. The data given here refer to studies carried out recently in many quarries (Zoppo, 1997 & Bergamasco, 1990), and the aim is to supply an order of magnitude of unit costs (US$/m^3) and information about the incidence of the main productive factors.

For the case represented in Figure 2, a comparison is made between the dynamic splitting method and diamond wire sawing; the volume of the primary block, as shown, is 512 m^3. In order to separate the bench, three cuts are required, assuming that there is not an easy way, while a vertical side has already been opened.

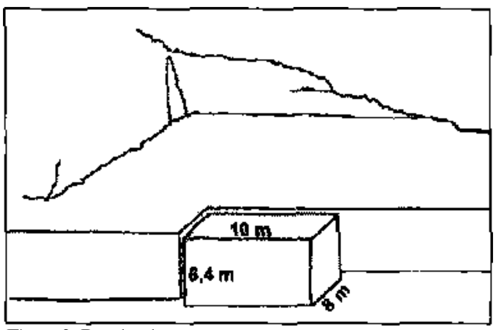

Figure 2. Bench scheme.

The main cost headings taken into account are: machinery depreciation, manpower, service, wear and energy costs. In Table 2, quarrying activities and items are given with the cost headings according to the cutting method.

Table 2. Main cost headings.

	Dynamic Splitting	Diamond wire saw
Machinery depreciation*	-Pneumatic drill** (small diameter 30-45 mm)	-Drill (bigger diameter); -Diamond wire saw
Manpower	-Drill placing; -Drilling; -Hole charging, -Priming -Blasting	-Dniling; -Closing wire loop inside holes; -Placing wire saw; -Cutting supervising
Service and wear	-Explosive; -Drilling items	-Diamond wire, -Drilling items; -Wire saw service
Energy	-Compressed air	-Electrical energy

* Only machinery used during cutting operations is considered Other machines, such as wheel loaders and excavators, are not taken into account because they are needed independently of the cutting method.

** Pneumatic drilling is considered here. It has lower investment costs but also a lower drilling speed compared to a hydraulic drill; hence, the global costs are nearly the same

The unit costs expected for bench cutting by dynamic splitting come to about 5.9 US$/m^3, while in the case of diamond wire sawing a cost of 18 US$/m^3 is obtained. The per cent incidence of different cost headings is illustrated in Figure 3

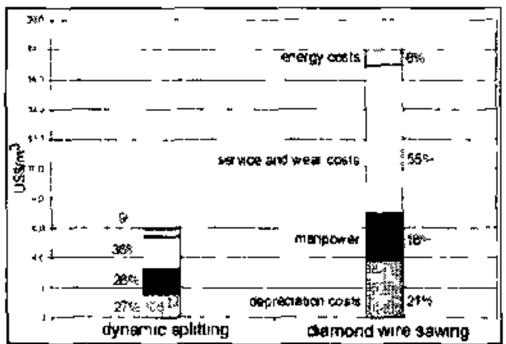

Figure 3 Per cent incidence of cost headings (US$/m^3)

As mentioned above, the choice of a specific technology should also take into account the commercial block price. Many operators agree on the point that explosive cutting causes a 7-10% waste of material due to cracks which may occur near the splitting surface, while only a 2-2.5% waste is produced by diamond wire sawing.

The real unit production costs of the two compared methods are plotted as a function of the unit price of the blocks m Figure 4, where a spoil of 7% is taken into account for the dynamic splitting method, while this is 2.5% for die diamond wire saw.

The data from the investigation show that primary cutting by dynamic splitting is about 60% cheaper than "pure" diamond wire sawing. However, at least part of the cost difference can be balanced by the better quality of the blocks obtained and by less production of waste. This last point represents a benefit whose importance grows as the commercial value of the product grows and, hence, while In low value stones splitting by explosive is the lower cost option, in high-value materials the wire option is preferable, as shown in Figure 4.

It should be considered that the drilling and blasting method for *hard* stone primary cutting will hardly provide great improvements, mainly because the productive cycle does not allow deep automation, thus keeping high labour costs. Moreover, even though mitigable, problems related to noise, vibrations and unexpected fly rock still impose restrictions on the method, especially close to towns or roads.

As far as diamond wire sawing is concerned, the wire itself is the biggest part of the total production cost, but substantial progress is still possible. For instance, research is being carried out on the optimal bead matrix for different rock types, the rubber coat quality to avoid metal cable wear, etc. Further efforts should be made to improve the safety conditions of diamond wire use; accidental wire breakages are still very dangerous because of wire lash and the throwing of beads or other metallic parts (Berry et al., 2000).

Finally, the global reliability and service performances of diamond wire could still be improved in abrasive stones.

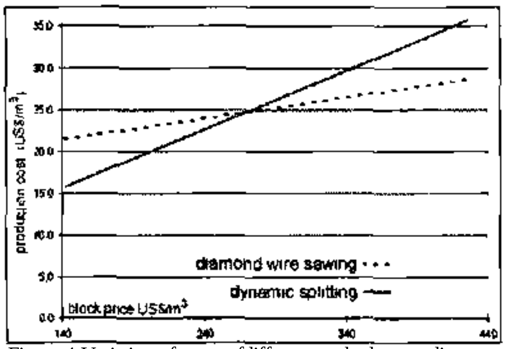

Figure 4 Variation of costs ofdifferent methods according to block price

4 EXPECTED IMPROVEMENTS

As detonating cord splitting is a simple and mature technique, some progress is expected only on the drilling side of the production process: more productive drills and, above all, more accurate guidance. As to diamond wire sawing, the main problem to be solved is the increase in service life with abrasive stones. Diamond is harder than any material and hence it can, in principle, cut anything, but cutting diamonds are held in place on beads by a metallic matrix, susceptible to wear and still perfectible as to binding power.

Wire saw beads fall into two basic categories: *electrodeposed* (a single layer of coarse diamonds is fastened to the bead by electrolytically deposed metal) and *impregnated* (a fine diamond/metal sintered layer is applied to the bead). The former type, more productive, cheaper but less durable, is commonly used with marbles, the latter, slower in action but longer lasting, with *hard* rocks.

By analysing the diamond grit recovered by chemical dissolution from the cuttings, it has been found that usually up to 40% is made up of diamonds not much smaller than original size, which means that a lot of unexploited diamonds are simply lost due to imperfect binding or to premature wear of the matrix. Indeed, manufacturers are concentrating on this point. Some success has been achieved: purposely made impregnation bead wires have already attained service lives of 10 to 12 m^2/m in gneisses. In *hard* stone cutting, diamond wire sawing is not yet completely competitive with detonating cord, however, as pointed out above, advances m wire performance are rapid and a lot of grämte quarrymen already use diamond wire sawing at least in part of the production process (Figure 5).


Figure 5 Side cut with diamond wire in a Sertzzo quarry

In practice, diamond wire is nearly always used with explosives (Figure 6). It is used especially to create *channels* in the rock mass or to make ample side cuts. Other cuts which definitely isolate the bench are obtained by the explosive method. At the moment, the application of mixed diamond wire-explosive technology allows better recovery in comparison with simple dynamic splitting, with a small cost increase. Therefore, it is necessary to pursue optimisation of this method in order to take advantage both of diamond wire's *precision* and possibility for automation, and the versatility of explosives. Where high-value dimension stones are concerned (e.g., Beola), sometimes the cut to create a smooth artificial easy way is also made with diamond wire in order to get higher slab recovery dunng further processing It has been noticed that blocks squared by explosives "lose" up to 10 crn on each side dunng the sawing process, producing considerable waste which, apart being a lost profit, represents an extra cost in dumping Moreover, dunng the sawing process, there is a spoil of abrasive gram and a remarkable waste of time at the beginning and at the end of slab cuts

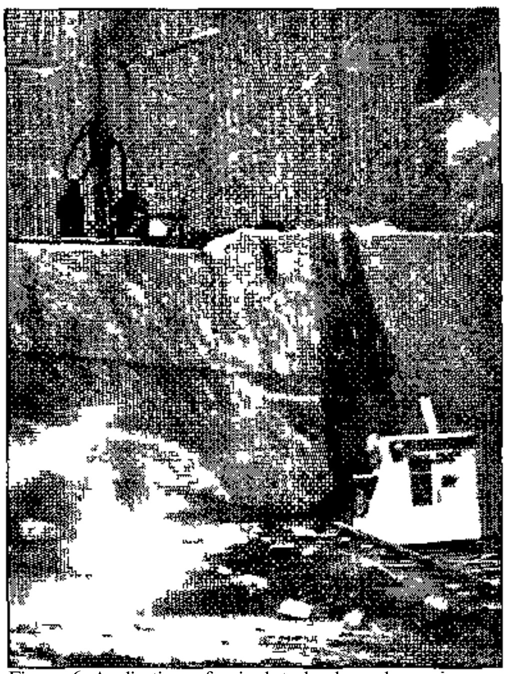

Figure 6 Application of mixed technology dynıı _ ı associated to diamond wire sawing ('Lusema ' stone)

In Table 4 below, some data referring to side cuts made by diamond wire in different *hard* stone quarnes are reported

Table 4 Side cuts in different *hard* stones

	Granite (Sardinia)	Gneiss (Lusema)	Sen220
Bead type	impregnated	impregnated	impregnated
Bead/metre	40	40	40
Bead $ (mm)	11	11	10
Wirelenglh	65	65	35
Drilling Φ (mm)	900	900	800
Wire speed (m/s)	24	23	24
Cut area (ra^2)	164	115	50
Productivity (m /h)	16	1 7	2
Service life (nT/m)	7 5	10	11

5 CONCLUSIONS

An evaluation of me ments of an exploitation method must take into due considération me ore recovery aspect (Del Greco et a1, 199^) An exception could be represented by the case of unlimited reserves of low value material located where environmental damage from exploitation can be considered negligible, but such conditions simply no longer exist

Even in the case of dimension stone exploitation, the only mining sector presently important in Italy, good deposits are uncommon or require costly development work, and must be fully exploited, hence, the best exploitation method does not always coincide with the cheapest excavation method

Investments per unit of in-situ resource can be very large the example can be given of a gneiss quarry, where a 500-m-long, 25-m^2-cross-section tunnel, costing around US$ 500000, had to be dnven and each cubic meter wasted of in principle marketable rock will consume, on the one hand, a share of this amount and will reduce, on the othei hand, the useful life of the expensive infrastructure

Therefore, in the dimension stone sector, more refined and, mtnnsically, more costly techniques are gaining importance

Table 3 Qualitative companson between main quarrying techniques used in Alpine *hard* stone quarries

Comparison elements	Detonating cord technique	Diamond wire technique	Detonating cord + diamond wire
Cut accuracy	Low	High	High
Cut productivity	High 7 lOmVh	Average 1-4 m Vh	High 10m^2/h
Energy consumption	Low	Average low	Average low
Capital cost (mech equipment)	Low	Average	Average
Tool consumption	Low	High	High
Environmental impact	High	Low	Average
Recovery on primary blocks	92%	98%	95%
Possibility of mechanisation process	Low	Average	Average low
Working conditions (safety)	Low	Average	Average*
Water consumption	Low	Average	Average
Influence of ore body shape and structure	Low	High	Average

* Block cut obtained by wire can be dangerous when working rack bodies with sloping easy splitting ways (danger of block displacement dunng cutting), in this case (quite common indeed) splitting by explosives is prepared for the back cut

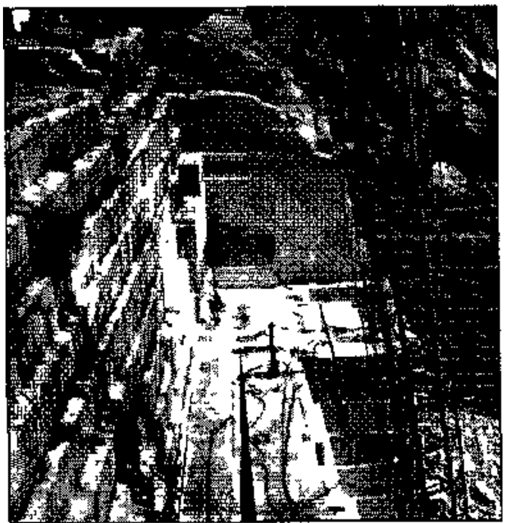

Figure 7 An Alpine granite quarry. Side cuts are made by diamond wire, while horizontal and front cutting are made by dynamic splitting

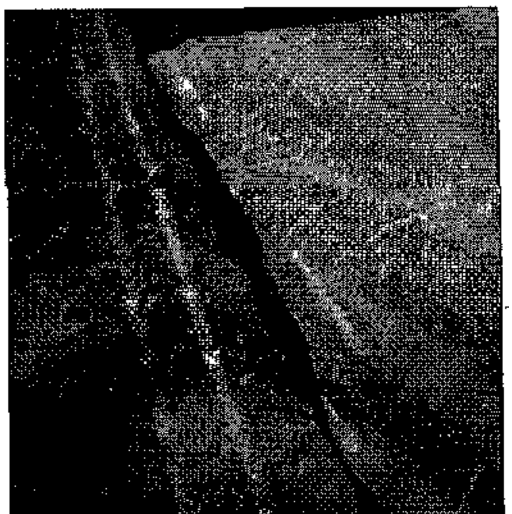

Figure 8 On the left an uneven surface cut by explosive half casts of the holes are well visible ("Verde" gneiss)
On the right a smooth surface created by diamond wire saw

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