Comparing alternative cutting technologies in marble quarries

M.MENEGAKI[*†], L. KAZATSANIDIS [‡]

[†] National Technical University of Athens, Greece
[‡] Dionyssos - Pentelikon Commercial & Industrial Marble Co S.A., Greece

Abstract. Technological evolution in marble cutting technologies has changed radically the production procedures. Today there are a lot of available choices making the selection of the proper equipment of strategic importance for the enterprises. The decision on the best available technology in each specific case, however, is a complicated task based on the particular characteristics of the rock to be extracted, as well as the assets of the company. The paper illustrates the case of the "Dionyssos" marble quarry located at the Penteli Mountain, Greece. Real–scale tests have been conducted in order to examine the performance of a chain saw machine, originally designated for underground quarrying, in the open pit quarry exploitation. The results of the new technique are compared with the results of the technique applied so far, namely, diamond wire cutting combined with soft blasting. The paper concludes with the advantages and disadvantages of each technique on a technical and economical basis.

Keywords: Marbles; Open pit quarrying; Cutting technologies

1. Introduction

Marble is probably the most popular ornamental stone in the world. The Ancient Greeks were among the first civilisations, which noticed the unique properties of this stone and have started exploiting it systematically. The extraction methods used in ancient times are not known. Nevertheless, according to findings and studies concerning the ancient quarries, the procedures did not differ much from those applied a few years ago, before the extensive use of the modern quarrying machinery (Laskaridis, 2004), since the main aim was always the extraction of a block from the solid rock with as little damage as possible.

At the ancient open quarries, the extraction of blocks was made by vertical and horizontal channels by saw and sand. Next, openings were made in order to insert iron or wooden wedges moistened with water to swell the wood and thus to cause the detachment of the marble block (Stellin et al., 2001). After excavating the block, the quarrymen had to hew the stone in order to get rid of the undesirable burden and to make transport handling easier.

Technological evolution in the extraction techniques resulted in significant improvements with regard to productivity and quality of the commercial blocks. The most significant technological development was put into practice when diamond wire cutting started being used in the ' 70s. Since then there is a

continuous attempt for further evolution based either on current technologies equipped with modern tools and parts (e.g. diamond wire configurations) or on completely new technologies like water-jet. The success of each technique differs in each quarry case, depending on the properties of the rock and the formation (Cardu & Loveral, 2004).

The paper examines the case of the "Dionyssos" marble open cast quarry, which is located at the Penteli Mountain. The company exploits a white to semi-white marble statigrafically overlying the famous "Pentelikon marble" also known as "Bianco di Pendeli" or "Marmo Greco Fino", which has been widely exploited during classic antiquity and the Hellenistic period and has been used in the construction of the Parthenon, the Erechtheus and the Propylaea on the Acropolis of Athens and other ancient Greek cities.

The quarrying method currently used at the surface operations is the diamond wire cutting combined with dynamic splitting in the horizontal surfaces. Lately the company was equipped with a new diamond chain saw originally designated for its underground quarrying operations, which take place in the area. The improved characteristics of the new equipment showed evidence of high cutting performance, creating prospects for its use in the open cast quarry in combination with diamond wire cutting. In this paper, the performance of this alternative technique is compared to the one applied so far based on a number of real-scale tests.

2. The "Dionyssos" marble quarry

The "Dionyssos" marble quarry is located 30 km from Athens at the north part of the Penteli mountain. The company "DIONYSSOS PENTELICON COM. & IND. MARBLE CO. S.A." that runs the quarry was founded in 1948. Nowadays it is a vertical organization that has managed to fully exploit the extracted material producing from slabs to marble dust and fine fillers.

2.1. Description of the main characteristics of "Dionyssos" marble

The Pentelikon mountain is part of the "Atticocycladic massif" and is composed of metamorphic rocks. The marble extracted from the "Dionyssos" quarry is white calcitic and belongs to the so-called "lower marble" horizon. The main tectonic characteristic of the quarry area is the existence of an upfold with a south-western to north-eastern orientation as well as the variety of natural fractures that cut into pieces the marble area, resulting in the low recovery rate of high quality marble blocks.

From mineralogical point of view the "Dionyssos" marble is a white fine-grained metamorphic marble with a saccharoidal microstructure. It shows a typical subpolygonal texture. It consists essentially of calcite (approximately 98%), containing also small amounts of quartz, muscovite, sericite and chlorite (0.5 % each). The largest calcite crystals range from 900 x 650 to 950 x 874 μm while the average grain size is approximately 430 μm (Cardani & Meda, 1999). Table 1 presents the chemical analysis and the physical properties of "Dionyssos" marble.

Table 1. Chemical analysis Physical properties of "Dionyssos" marble

Chemical analysis		Physical properties	
CaO	54.80%	Apparent specific weight	2.717 kp/m^3
MgO	1.55%	Porosity	0.371 % vol.
SiO_2	1.10%	Water absorption coefficient	0.11 % wt.
Fe_2O_3	0.14%	Compressive strength	1136 kp/cm^2
Al_2O_3	0.20%	Modulus of rapture	196 kp/cm^2
K_2O	0.09%	Abrasion resistance (after 1000 m)	6.68 mm
Na_2O	0.04%	Microhardness (Knoop)	130.4 kp/mm^2
MnO	0.02%	Modulus of elasticity	583.3 tn/cm^2
CO_2	43.05%		

2.2. Exploitation method and equipment

The exploitation in the quarry is carried out by open pit and underground methods. Underground quarrying of marble is performed by the room and pillar method. During the development phase chain saw is used in order to make the first cut in absence of free surfaces, while for the excavation of marble blocks as the quarry develops to the lower horizons, chain sawing is combined with diamond-wire cutting.

The Fantini GU70 chain saw machine used in underground quarrying is self moving on tracks and the cutting arm can get different positions in order to make horizontal and vertical cuts on different planes and "back cut" cuttings. The effective cutting length of the machine is 2 m. Lately, the specific chain saw model was replaced by the Fantini GU70-R model, the effective cutting length of which is 2.8 m. Another essential difference of the new chain saw machine is the widening shape of the arm (Figure 1), allowing easy cutting at the final cutting stage, without the need of swivelling the arm. The cutting tools are made in both models of polycrystalline diamonds (PCD), differing however in the shape. The square tools attached in the new model improve the cutting speed (8 m^2/h instead of 5 m^2/h achieved by the old machine). Moreover, when a cutting edge of the tool is rubbed it can be readjusted to the chain with a new orientation so as to achieve optimum cuts during the lifetime of the tools.

Figure 1. The Fantini GU70-R arm

The open pit quarrying method applied is by vertical benches of 6 m height. The dimensions of the primary detached marble blocks are averagely 10x4x6 m^3. Taking into consideration the capacity of the mechanical equipment, efforts are being made to maximize as much as possible the dimensions of initial blocks, so as to minimize technical cuttings and thus to increase the recovery rate of the highly fractured rock.

The detachment of primary rock is performed by drilling and diamond-wire techniques, as well as by soft blasting of horizontal cuts. More specifically, horizontal and vertical holes of 90 mm diameter are drilled using a bohler crawler with DTH hammer so as for the diamond wire to pass through and make the cut. The linear wire speed of the diamond wire cutter (model: Benetti VIP 910) is 35 m/s and the average production achieved is approximately 10 m^2/h. The intense schistosity of the rock allows for soft blasting as far as horizontal cuts are concerned, without causing any damage to the intact marble. For the soft blasting, parallel horizontal holes are drilled at a distance of 25 cm from each other, which are then charged with detonating penta-erythrite (12 gr PNT/m) and fired using a common cap and safety fuse. The extraction of the block is then carried out using an excavator with ripper, making also use of hydro bags in order to ease the procedure.

3. Investigation on the possible use of the chain saw machine in the open pit quarrying

The improved performance of the new chain saw model in underground quarrying showed evidence of potential use in open pit quarrying. The main idea was to use chain sawing for horizontal cuttings instead of the soft blasting. After a lot of trials in the open pit quarrying a comparative analysis has been conducted on a technical and economical basis.

The cut of primary blocks using the combined method of diamond-wire cutting with soft blasting consists of 3 sub-blocks, the dimensions of each of which were 15x3x6 m^3 (Figure 2).

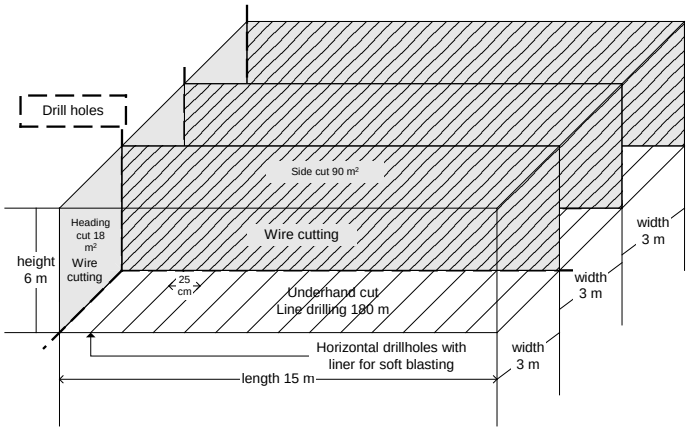

Figure 2. Marble blocks produced using wire cutting combined with line drilling

For the method of diamond wire cutting combined with chain sawing, the dimensions of the initial blocks were 12x 2.8x6 m^3 due to the limitation of the cutting depth (Figure 3).

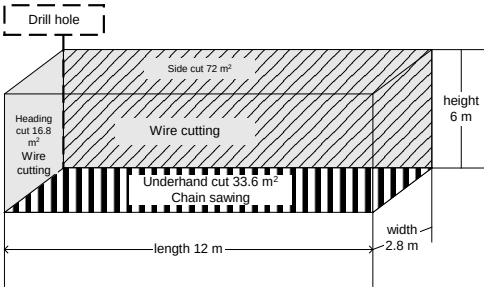

Figure 3. Marble block produced using wire cutting combined and chain sawing

In order to compare the results, the values produced were calculated per unit (m^2 or m). The parameters of cost taken into consideration were:

- the depreciation cost for an estimated life of 5 years for each machine,
- the operating costs including the cost of energy, wear parts and maintenance
- the operating labor cost.

For the extraction of the marble block two operators are needed and the daily labor cost of each is 100 €. The energy unit cost is 0.075€/Kwh and the water cost (purchase and transportation) is 4€/ m^3. The scheduled working days are 220 annually.

The vertical drilling in the case of diamond wire cutting requires 3 drills of 6 m each for the side cuts and one drill of 6 m for the heading cut. The success percentage of vertical drilling is 50% meaning that for each vertical drilling 2 holes are usually drilled in order to meet horizontal drill holes.

As for the wear parts, the following assumptions were made:

- The lifetime of a 60 m diamond wire is 3,600 m^2 of cutting and the replacement of the cutting elements is carried out after 900 m^2 of cutting.
- The lifetime of drill pipes is 1,200 m of drilling.
- The water consumption for wire cutting is from 15 to 25 lt/min.

Table 3 presents the purchase price, the daily usage, the production rate and the annual depreciation cost for each machine.

Table 3. Cost parameters of the equipment

	Purchase price	Daily usage	Production rate	Annual production rate	Annual depreciation cost
Chain saw (Fantini GU-70/R)	340,000 €	5 h	8 m^2/h	8,800 m^2	68,000 €
Diamond-wire cut (Benetti VIP 910)	27,000 €	5 h	10 m^2/h	11,000 m^2	5,400 €
Crawler drill	150,000 €		50 m/day	11,000 m	30,000 €
Liner (Tamrock)	150,000 €		150 m/day	33,000 m	30,000 €
Crane	60,000 €	5 h		1,100 h	12,000 €

Based on the above parameters the cost per unit for each machine used during the extraction procedure was estimated. The results are given in Table 4. According to the cost per unit estimations the extraction cost using the above mentioned techniques was calculated, as shown in Table 5.

Table 4. Estimation of the cost of each machine per unit of cut block

	Depreciation cost	Energy cost	Labor cost	Wear parts and maintenance cost	Total cost per unit of cut block
Chain saw (Fantini GU-70/R)	7.73 €/m^2	0.53 €/m^2	2.5 €/m^2	6.60 €/m^2	17.35 €/m^2
Diamond-wire cut (Benetti VIP 910)	0.49 €/m^2	0.25 €/m^2	1.28 €/m^2	0.38 €/m^2	2.41 €/m^2
Crawler drill	2.73 €/m		7.20 €/m		9.93 €/m
Liner (Tamrock)	0.91 €/m		1.74 €/m		2.65 €/m
Crane	10.91 €/h		20 €/h		30.91 €/h

Table 5. Calculation of the cost for the extraction of blocks

Works to be done	Wire cutting combined with soft blasting			Wire cutting combined with chain sawing		
	Length, surface, volume or hours	Cost per unit	Total cost for blocks	Length, surface, volume or hours	Cost per unit	Total cost for blocks
Diamond wire cutting (side cut)	270 m^2	2.41 €/m^2	650.70 €	72 m^2	2.41 €/m^2	173.52 €
Diamond wire cutting (heading cut)	54 m^2	2.41 €/m^2	130.14 €	16.8 m^2	2.41 €/m^2	40.49 €
Chain sawing				33.6 m^2	17.35 €/m^2	582.96 €
Horizontal drilling (heading cut)	45 m	9.93 €/m	446.85 €			
Horizontal drilling (side cut)	9 m	9.93 €/m	89.37 €			
Vertical drilling (side cut)	36 m	9.93 €/m	357.48 €			
Vertical drilling (heading cut)	12 m	9.93 €/m	119.16 €	6 m	9.93 €/m	59.58 €
Water consumption	38.88 m^3	4 €/m^3	155.52 €	10.66 m^3	4 €/m^3	42.64 €
Line drilling	540 m	2.65 €/m	1431.00 €			
Fuse needed	1100 m	0.17 €/m	187.00 €			
Charge time needed	0.75 h	12.5 €/h	9.38 €			
Time for picking up the wire	6 h		75.00 €	1 h	12.5 €/h	12.5 €
Crane usage	3 h	30.91 €/h	92.73 €	1.5 h	30.91 €/h	46.37 €
Total cost	**3,744.33 €**			**958.05 €**		
Total cost /m^2	**4.62 €**			**4.75 €**		

According to the results produced by the comparison of the two alternative methods, the use of the chain saw machine in the open pit quarry is possible, since the increase in cutting cost per square meter of block (approximately 2.8 %) is not prohibitive. This is due to the fact that drilling works are limited when the chain saw is used resulting in the significant reduction of the preparation time needed. Figure 4 presents the cost allocation for each of the alternative techniques.

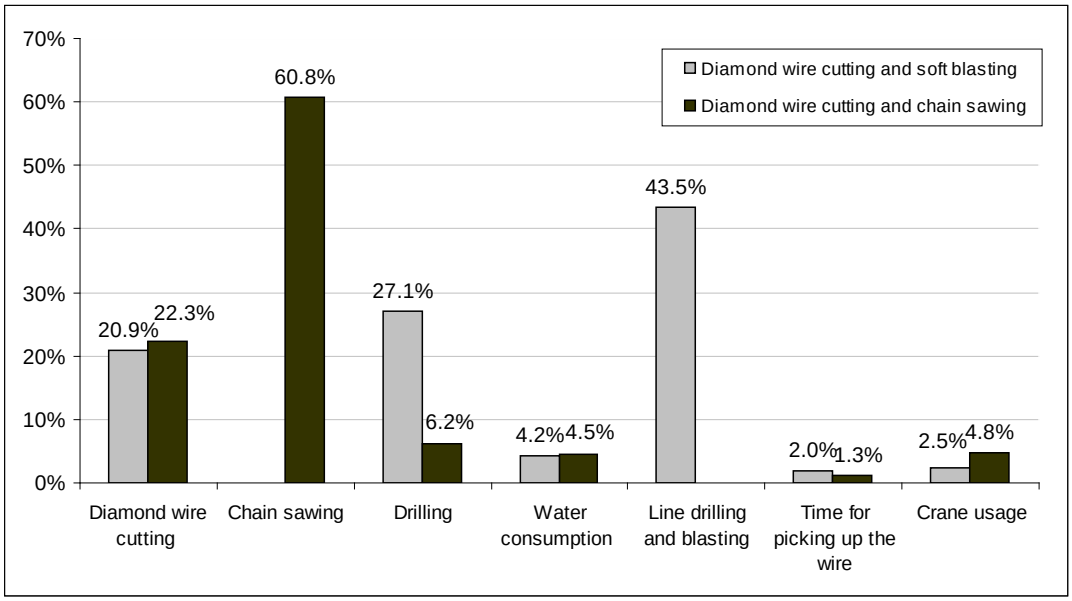

Figure 4: Cost allocation for each of the techniques examined

4. Conclusions – Discussion

Technological progress in dimension stone quarrying gave rise to the application of a lot of different techniques for performing different operational phases in a safe and productive way based on the specific characteristics of each quarry. Diamond wire cutters marked a new era in the way of working in marble quarries. Nowadays the cutting with diamond wire is a common technology in most of marble quarries. Despite its versatility in use and its contribution to the reduction of marble wastes, diamond wire cutting necessitates precise drilling, skilled manpower and continuous supply of water.

On the other hand the chain saw technology comes from the development of machines assigned to underground quarrying. The main advantages of its use are the simplicity of operation, meaning that there is no need for skilled personnel, and the regularity and planarity of the cut produced. The reduced depth of cutting though, limited to the length of the arm, as well as the relatively low cutting speed, consist the main restrictions for its use in open pit quarrying. Technological evolution has led to the construction of chain saw machines with improved characteristics, especially with regard to cutting speed. Although 6 m long arms are available

nowadays, their use is restricted to vertical cuts and thus, the length of the arm is still a problem.

The investigation of the introduction of the new chain saw machine in the production procedure of the "Dionyssos" marble open pit quarrying revealed the possibility of its use at the quarry site on a standard basis, since its cutting length proved to be adequate. This is mainly due to the highly fractured rock mass that does not allow for deep cuts anyway.

The cost per square meter of extracted block not only is affordable but also comparable to the cost produced by the method used until now, since the total cost increase is approximately 2.8%.

This additional cost is counterbalanced by the advantages obtained over the current method applied. More specifically, chain sawing allows for more precise cuts producing rectangular blocks with reduced losses, since there are not drilling deviations as in the case of wire cutting combined with soft blasting. The planes produced by wire cutting combined with chain sawing are usually adjoining and thus there is no chance that a section of uncut marble will be left, resulting in the wider breakage of the robust marble block. The perfect planar and wide cut achieved by the chain saw machine, facilitates among other, the truck movement diminishing the work load. Finally, the performance of the chain saw machine has been tested in vertical cuts, showing evidence of a potential more extended use in the open pit quarry.

References

1. Cardani, G. and Meda, A., Flexural strength and notch sensitivity in natural building stones: Carrara and Dionysos marble, *Construction and Building Materials,* 13, 1999, pp. 393-403 (Elsevier Science Ltd.).
2. Cardu, M., Loveral, E., Quarrying methods and cutting technique, in Optimising Quarrying Techniques and Practices, edited by Terezopoulos and Paspaliaris, pp. 1-28,2004, (OSNET: Athens)
3. Laskaridis, K., Greek marble through the ages: an overview of geology and the today stone sector, in Dimension stone, edited by Přikryl, pp. 67-72, 2004, (Taylor & Francis Group: London)
4. Stellin, A.Jr., Hennies, W.T., Soares, L. And Fujimura, F., Dimension Stone Block Extraction by Steel Wires, Proceedings of the 10th international Symposium on Mine planning and Equipment *Selection,* 2001, pp. 215-222.