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ARMINES - CENTRE DE GEOLOGIE DE L'INGENIEUR (FRANCE)

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IMPROVEMENT OF PRODUCTIVITY IN QUARRYING DIMENSION STONE USING NEW DRILLING AND BLASTING TECHNIQUES

J.A. Sanchidrián, P. García-Bermúdez (UEE, Madrid, Spain)
C. Tsoutrelis, G. Exadaktylos (NTUA, Athens, Greece)
R. Cojean, J.A. Fleurisson (ARMINES, Paris, France)
J. Tsimidakis, C. Rogakis (DIONYSSOS MARBLE, Athens, Greece)

ABSTRACT

Ornamental stone quarrying by drill and blast methods is surveyed. Although a traditional technique, significant improvements are identified along the course of the investigation.

A method for analysis of rock masses, with particular attention to systems of discontinuities, has been cast, so that planning of quarrying works is made in a sound and systematic way.

Numerical modeling has been used to get an insight of the action of explosive on the rock in the typically uncoupled blasting; both dynamic and quasi-static simulations were carried out in a variety of blasthole geometries (cylindrical and notched) and explosive charges. Preliminary critical (maximum) borehole spacings were obtained by modeling.

Laboratory and small scale tests in marble and granite have been carried out to investigate the effect of explosive charge, coupling ratio, notches and fill material on the quality of the cut and allowable blasthole spacing. Some innovative methods, such as blasthole lining with slotted tubes have also been tested in marble. The positive effect of decked charges of black powder has also been observed in granite cutting.

Some case studies have been analyzed in detail, and better *use* of drill and blast has been put into practice: decking of black powder in granite primary and secondary blasting, notched holes in granite squaring and in marble secondary blasting. An evaluation of the benefits of these techniques is presented.

Practical considerations are given for blast cutting in granite and marble. Suitable drilling equipment is found of great importance for good quality blasting, mostly for using notched drillholes efficiently. A preliminary design of *a* drill-and-notch machine is shown.

A computer program for the design of quarry operations is presented.

INTRODUCTION

Ornamental stone quarrying is a relevant sector in the mining field of activity, particularly in Southern Europe countries. Two methods are, basically, used in ornamental stone quarries: mechanical, such as diamond wire and saw, and controlled blasting. Other methods are used, though in a minor and most often complementary way, such as the jet flame.

Diamond wire and saws are commonly used in quarrying of soft rocks, such as marble, while controlled blasting is generally used for harder rocks, such as granites. Nevertheless, most exploitations make use of both techniques, one of them being dominant depending on the hardness of the rock. Economic reasons may well lead to the preference of one method or the other, as investments needed for mechanical cutting are higher than for drilling and blasting.

In most of the quarries, large blocks (dimensions may vary as much as 5 to 20 m long, 5 to 12 m high and 4 to 30 m in depth) are first extracted (see Fig. 1). For it, vertical planes normal to the bench face are cut using diamond saw machines or diamond wire. The remaining two planes are commonly cut by drilling and blasting. Boreholes are almost universally 28-34 mm in diameter, charged with detonating cord and very often with black powder as bottom charge. Detonating cords of 6 to 12 g/m weight are the more frequently used. Stemming is done by filling the boreholes with water, so that a certain coupling between the explosive and the rock is enabled. In some cases, as in marble cutting, the explosive must be fully uncoupled to the rock for the shock pressure to be reduced, and no stemming is used at all. Blasthole spacing ranges from 20-25 cm in marble, without stemming, to 30-45 cm in granite, with water stemming. Holes are, sometimes, alternatively left uncharged between charged holes. Lifters (horizontal blastholes) may, when weakness plane is horizontal in granite quarries, be reduced to a large diameter blasthole alone.

The secondary cutting (subdivision of the large primary blocks) is done in hard rock, again, by drilling and blasting along successive rows of blastholes. Further subdivision into commercial blocks may be done by either drilling and blasting or by using wedges. In softer rocks, such as marble, diamond saw and disk cutters are most often used for this phases.

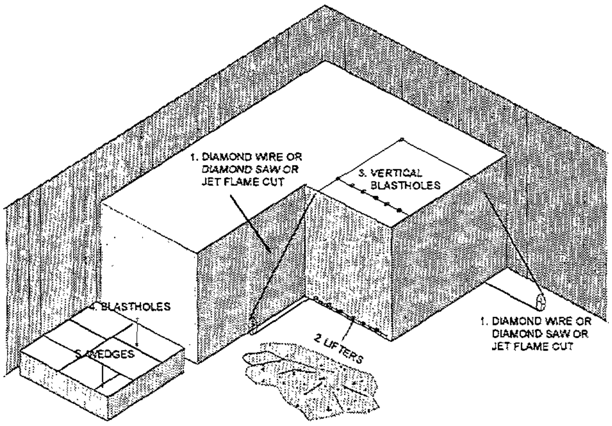


Figure 1. Typical dimension stone quarrying sequence.

The improvement of the cutting process by blasting means:

- To reduce the drilling and blasting cost, by increasing the boreholes spacing, or by implementing better drilling devices.
- To reduce the waste of valuable rock.

These two goals involve a number of variables and aspects, namely:

- Blasthole spacing, which is always a balance between drilling cost and quality of the cut.
- Amount and distribution of the charge. Different detonating cords and black powder are customary. Filling of the boreholes can be either water, sand or none. Some boreholes may be left uncharged at alternate positions in the borehole line. Use of explosives can be significantly improved if loading operation is made easier.
- Directionality of the blasting. Cut blasting is most often done along weakness planes of the rock. There is not much chance to influence on this in practice, as weakness planes are taken into account when planning works at every quarry.
- Special drilling, such as notched holes, is a known technique that allows for a wider holes spacing. Nevertheless, it is not of general use in the quarries; improvements on drilling equipment could significantly enhance its use.

Optimum parameters for a cutting blast are highly dependent on the properties of the rock and the direction of the cut. General solutions are hard to state as the variety of geologic situations is rather vast. Hence, efforts were concentrated in obtaining, at least, as general as possible methodologies and directions to follow.

DESCRIPTION OF ROCK MASSES

This work is focused on granite and marble, the first being a typical hard rock and the latter a soft one. Mechanical properties of those are summarized in Table 1.

A detailed survey was carried out in certain granite and marble quarries in Spain and Greece, in order to collect data on the controlled blasting techniques used in the various phases of the extraction process. A specific methodology was implemented to obtain a good description of the sets of discontinuities and structure of the rock masses; 3D geometrical models and serial sections were obtained using SIMBLOC and VISIBLOC programs, making cutting planes apparent. Fig. 2 shows a sample output of SIMBLOC code, where sets of discontinuities and preference directions of cut are shown.

An evaluation of the damaged zone around blastholes was performed using brazilian, bending and ultrasonic tests. Elastic properties of the rock were obtained as a function of the distance to the blasthole wall. As an example, Table 2 shows the variation of the tensile strength of a marble from brazilian and bending tests.

Table 1. Mechanical properties of granite and marble.

	GRANITES		MARBLES		
	Blanco Castilla	Blanco Berrocal	Dionyssos	Volakas	Naxos
Uniaxial Compressive strength (MPa)	145	196	70-79	121-126	40-49
Tensile strength (MPa)	9.75	13.18	5,9-11.5	6.1-11.5	3.3-5.2
Bending strength (MPa)	15.1	15.9	9.3-25.6	8.2-10.2	12.8-17.7
Young's Modulus (GPa)	55.1	67.3	42.5-47.1	56-62	36.8-41.0
Poisson's Ratio	0.27	0.28	0,25-0.32	0.28-0.38	0.17-0.26
Density (g/cm^3)	2.69	2.59	2,69	2,82	2.69

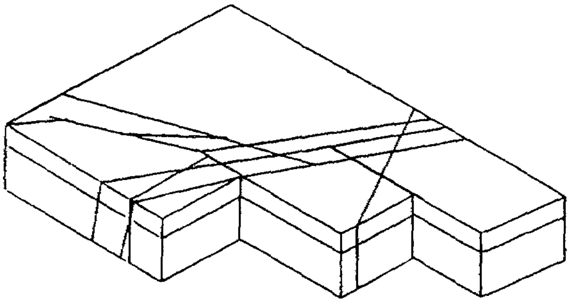


Figure 2. SIMBLOC section of a quarry bench.

NUMERICAL MODELING

A mathematical model able to predict *a priori* the blasting variables (i.e., blasthole spacing and charge), is probably out of reach, considering the large number of uncertainties that are always present when describing a rock mass. Nevertheless, numerical modeling has been used as a means to obtain a deep understanding of the interaction of explosive and rock, and of the cutting process itself. This, in turn, allows a reasonable evaluation of the experimental results.

Both rock and explosive materials must be modeled. The use of explosives strongly calls for dynamic simulation, due to the highly transient phenomena induced upon the rock mass. However, it is possible, specially at blasting in ornamental quarries, to study the dynamic fracture process apart from the gas pressure process. As a matter of fact, the shock wave is intentionally reduced by using explosives with low detonation pressure or low coupling ratios. The dynamic effects are considerably reduced and the gas pressure action can be considered as the main physical phenomenon involved in blasting. In any case, the possible presence of microcracks around the blasthole has to be taken into account.

Special geometries (notched holes} and influence of anisotropy were also topics under study from the modeling point of view.

a) Dynamic simulation with DYNA2D

The simulation of explosive/air interaction was a first objective of the modeling task. Then, the simulation of the rock fracturing process was pursued, so that blasting patterns could be analyzed to determine optimum parameters (blasthole spacing).

The explosive/air interaction has been dynamically modeled using a JWL-type equation of state (Lee et ai., 1968) for the explosive. JWL parameters for detonating cord of different PETN weights were calculated. A DYNA2D-standard material model (pseudo tensor geological) was used for the simulation of the rock (Hallquist, 1988).

The explosive/air interaction cannot be simulated in a direct way using a lagrangian code as DYNA2D, due to the large deformation suffered by the air elements and the involved numerical problems. in order to solve this situation, the explosive and air were simulated as a whole. For that purpose, a JWL-type equation of state was used for a “mock” explosive filling the borehole, reproducing the pressure histories computed in a real explosive/air interaction over the borehole wall. The detonation and JWL parameters for this “mock” explosive were obtained considering three different PETN detonating cords of 3, 6 and 12 g/m within a 32 mm borehole.

When water is filling the borehole, standard JWL parameters were used for PETN (Dobratz, 1985). Shock equation of state parameters for water were taken from Mader (1 989).

Simulations were carried out to determine the critical distance between blastholes to produce the rock cutting for different 2D blasthole patterns. The detonation action on the borehole wall was summed up by the pressure history obtained in this waii from a 3D -2D axisymmetric- simulation (see Fig. 3). Blastholes delays were set in the model, derived from the velocity of detonation of the detonating cord and the spacing (1.5 μs per centimeter spacing). A strain-based criterion was chosen to determine the critical distances, so that rock cutting is assumed if ail the material elements in the borehole line have at any time a transversal strain greater than a threshold, that is computed from the geomechanic characteristics of each rock.

Figs. 4 and 5 show two samples of strain contours normal to the blasthole line; cut is obtained in the first (6 *g/m* detonating cord, 38 cm spacing) and no cut in the latter (6 g/m detonating cord, 44 cm spacing). Critical spacings (minimum at which cut is produced) obtained are summarized in Table 3. They agree quite well with available experimental data.

Table 2. Tensile strength of damaged marble.

Distance from blasthole wall (cm)	0	2.9	5.3	5.8	8.7	10.6	11.6	14.5	15.9	17.4	21.2
Tensile strength, brazilian test (MPa)	5.3	6.2		7.0	6.3		7,4	7.7		7.0	
Tensile strength, bending test (MPa)	7.6		13.1			16.3			96.2		164

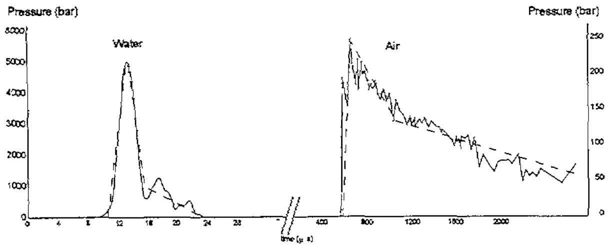


Figure 3. Pressure in the borehole wall at a point 400 cm down from the initiation point (collar); 6 g/m detonating cord. Left: water filling the borehole; right: air in the borehole.

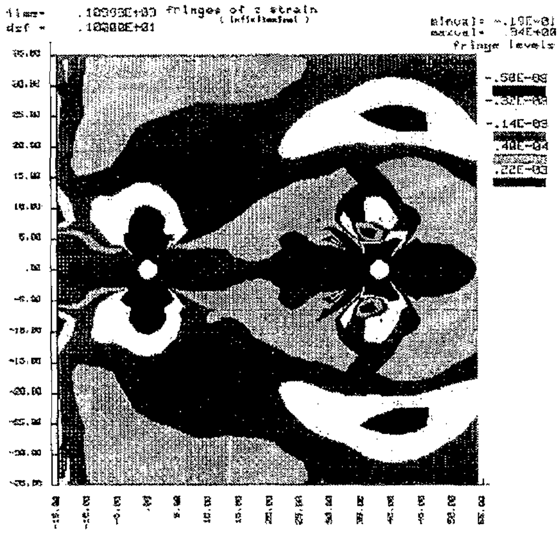


Figure 4. Fringes of *z* strain (normal to the borehole line) in granite in the vicinity of two 32 mm diameter boreholes, 38 cm apart. 6 g/m detonating cord used; water *in* borehole. Time is 110 µs after detonation of the borehole in the left. Cut is obtained.

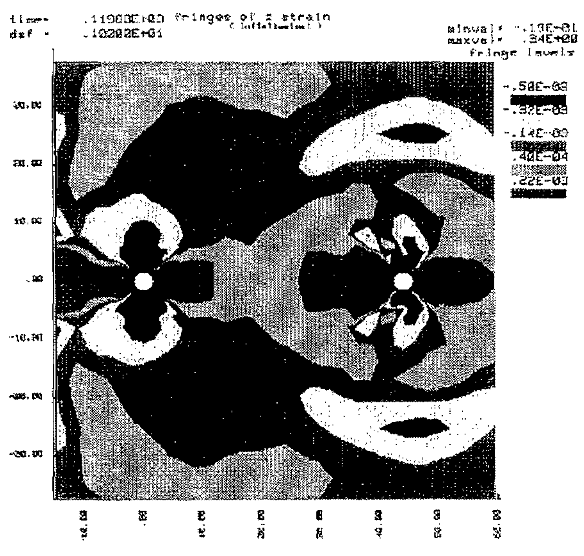


Figure 5. Same as figure 4, but boreholes 44 cm apart; time is 120 µs. No cut is obtained.

Table 3. Critical spacings (cm) in granite obtained with numerical modeling.

		Cylindrical holes		Notched holes	
		Coupling		Coupling	
		Water	Air	Water	Air
Detonating cord weight (g/m)	3	30		31	
	6	40	20	41	30
	12	50	36		44

The importance of the use of notches, or the presence of flaws in the material is apparent for uncoupled holes ("air coupling"), but it is not numerically justified for blastholes filled with water critical distance has a negligible increase in notched holes when water is in the holes, while it increases significantly when fully uncoupled blasting is used.

b) Quasi-static simulation with FLAC

A parallel analysis to the one just described has been undertaken using **FLAC** code (Itasca, 1993), the analysis based on the quasi-static action of the detonation products. The fracture process itself, the influence of rock anisotropy and the geometry of the notched borehole were analyzed.

First of all, a parametric study concerning the quasi-static expansion of cylindrical cavities with or without cracks and notches has been carried out in order to analyze the role of mechanical behavior and anisotropy of rock material, boundary conditions and notches geometry, According to the fracture process theory, the induced fracture propagates by opening the material in tension, and therefore, the main mechanical parameter is the tensile strength of rock material. Concerning the notch geometry, the length plays a major role by increasing the tensile stresses at its tip, which promotes the fracture expansion. It appears that the width of the notch has no significant influence, and that the U-shaped notch is the most appropriate. Moreover, the presence of notches leads to decrease the tangential stress at the tip of possible micro-cracks located around the hole. This phenomenon will reduce the possibility of fracture propagation at the tip of micro-cracks, and on the contrary will make easier the fracture propagation at the tip of the notch.

Then, computer simulations were performed in order to compare the numerical results with the ones from laboratory testings (described in the next section).

Numerous parameters that affect the studied problem were investigated. Coupling ratios ranging from 8 to 32 % and notch lengths of 1 and 3 mm long **were** used. In each *case,* computed and experimental maximum induced fracture lengths were compared, as show in Fig. 6.

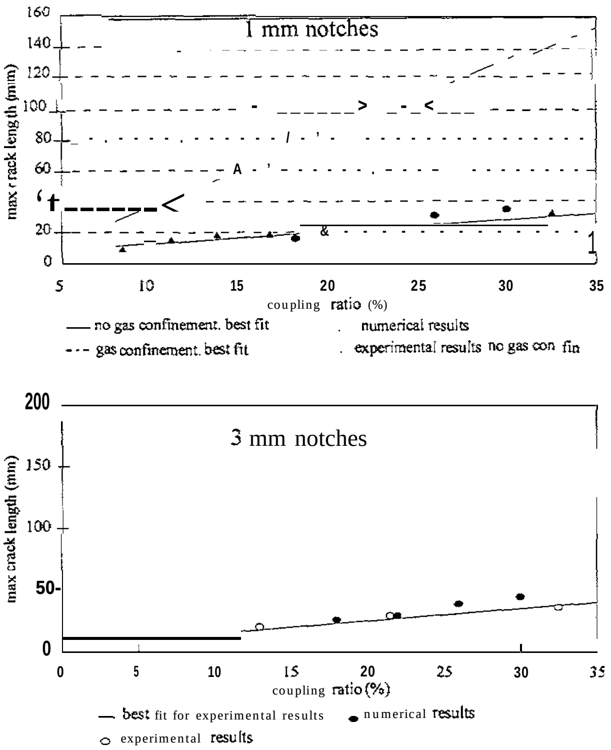


Figure 6. Comparison between numerical and experimental results on Plexiglas testings.

As the numerical model used does not take into account the gas penetration in the propagating crack, the numerical results are very consistent with the no gas confinement ones, provided that the coupling ratio is greater than 15 %. Under this value, the gas pressure is lower than the plexiglas tensile strength, and consequently fracture does not open because the model assumes a perfectly homogeneous and isotropic material. The small experimentally observed cracks could come from local heterogeneities or from extension of microcracks due to drilling.

Taking into account an elastic plastic law (Mohr-Coulomb criterion) with a tensile strength, it is possible to initiate the fracture process between two boreholes by using the computer code FLAC. The objective is to define a critical distance between boreholes as the greatest spacing required to open a continuous fracture between the two boreholes.

A parametric analysis was performed concerning the role of the two main parameters involved in the fracture process: the tensile strength of rock material and the opposite notches length. The borehole diameter is 34 mm and the gas pressure is 25 MPa which are both usual values in ornamental quarries. The whole results underline particularly the positive contribution of notches on the fractures process. Even short notches (15 mm) could increase the critical distance by more than 50 % in the considered range of tensile strength between 7.5 and 17.5 MPa, which corresponds to common values for ornamental rocks (see Figs. 7 and 8).

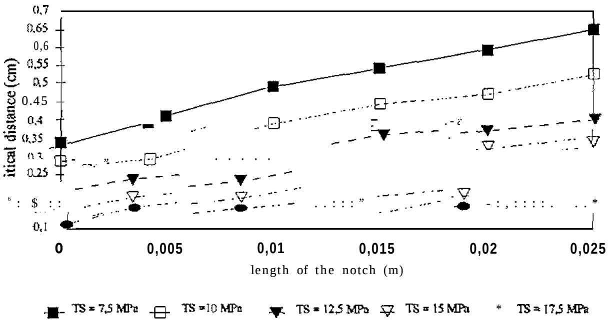


Figure 7. Critical distance as a function of the notches length for various tensile strengths between 7.5 and 15 MPa (isotropic elastic plastic model).

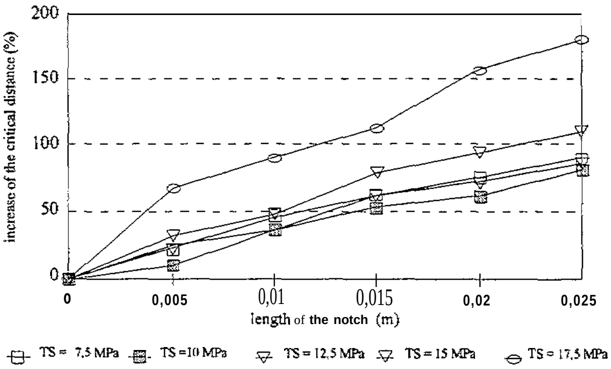


Figure 8. Increase of the critical distance as a function of the length of notch for various tensile strengths between 7.5 and 15 MPa (isotropic elastic plastic model).

This result is of paramount importance because that means that the use of notches can bring significant savings in drilling operations.

In order to give practical guidelines to assess the spacing between boreholes, two formulae were fitted with the numerical results:

- for unnotched boreholes:

$$CD = 0.51 - 0.023 \cdot TS$$

- for notched boreholes:

$$CD = 14.2\ l_r^{0.28}/TS$$

where

CD is the critical distance (m)
TS is the tensile strength (MPa)
l_r is the notch length (m).

The influence of boundary conditions was also analyzed as a function of the distance between the borehole line and the free face. Over a 2 m wide bench, which is a minimum value in primary cutting, boundary conditions have no influence on the critical distance.

The choice of an isotropic medium to represent the rock mass is obviously an idealization of the reality. The following simulations were implemented to analyze the efficiency of notched boreholes in relation with the anisotropy of the rock.

First of all, local heterogeneities as weak zones (with very low tensile strength) were included in the rock material model at the edge of the notched borehole. The presence of local flaws as well as their location does not effect the initiation of the fracture process which starts in the direction of the notch. On the contrary, when the length of the heterogeneity is increased (vein or discontinuity connected with the borehole), the fracture expands mainly in its direction. This phenomenon was expected because theory predicts that the longest crack always propagates first.

In a second stage, full anisotropic model was simulated using the FLAC ubiquitous joint model. This is an anisotropic plasticity model which assumes a series of weak planes embedded in a Mohr-Coulomb solid. Yield may occur in either the solid or in the weak plane by overcoming tensile strength or Mohr-Coulomb yield criterion. Results are summarized in Fig. 9.

Provided the tensile strength ratio (joint to rock) is not too small, the presence of two opposite notches counterbalances the effect of the anisotropy and the fractures propagate mainly in the direction of the notches. However, parasitic cracks are liable to grow in the direction of the anisotropy, and the more the notches deviate from the direction of the anisotropy, the greater they are.

Moreover, in these favorable cases, the spacing between boreholes has to be adapted to the respective tensile strength of rock material and weak planes regarding the angle between both directions of anisotropy and notches. The other mechanical parameters such as cohesion and friction angle do not play a significant role.

Anyway, these semi-quantitative results underline the importance of an accurate in-situ identification of the anisotropy and a good determination of the anisotropic mechanical properties, in particular the tensile strength.

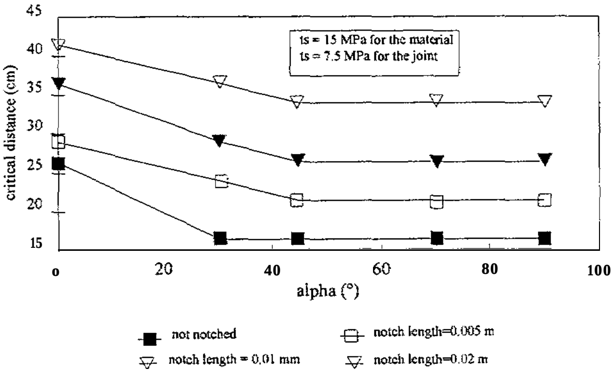


Figure 9. Influence of the direction of anisotropy on the critical distance (ubiquitous joint model).

LABORATORY TESTS IN PLEXIGLAS AND MARBLE

A number of non-conventional techniques applied to dimension stone cutting have been described in the literature, namely:

A dummy hole between two live holes
- Lines of dummy holes
- Prenotched boreholes
- Charge holders with slits
- Charge holders with wedges
- Charge holders with a concentrated force
- Charge holders with two stages of detonation.

Laboratory experiments were split in two series: The first one with plexiglas which, being isotropic, homogeneous, brittle and transparent offers many advantages as reference material. The second involved three different types of marble; tests in this series were based on the plexiglas results. The parameters investigated were:

- Coupling ratio
- Gas action
- Geometry of notches
- Introduction of water and other fill material between the decoupled explosive and the blasthole wall.

The flow chart of Fig. 10 presents the series of tests and parameters investigated in the laboratory scale using plexiglas as the testing material. As it can be seen from this chart two main lines of testing were followed:

(1) plexiglas models with a single blasthole; and
(2) plexiglas models with three blastholes in a row.

Similar conditions were applied to tests on marble. A number of conclusions were drawn from this experimental work:

- Single hole blasting experiments have showed that coupling ratio D_e/D is critical for the development of undesired fracturing around the blastholes (see Fig. 11).
- The use of water as a filling substance in the region between the hole wall and the explosive increases appreciably the relative participation of the shockwave in the fracturing process, as can be seen from Fig. 12.
- The gas pressure which succeeds the shock wave action is mostly responsible for the final crack lengths due to blasting. The shockwave only creates a dense network of micro-cracks around the blasthole which are further extended in much greater lengths by the pressure of the gaseous products. This means that stemming of the blastholes is of major

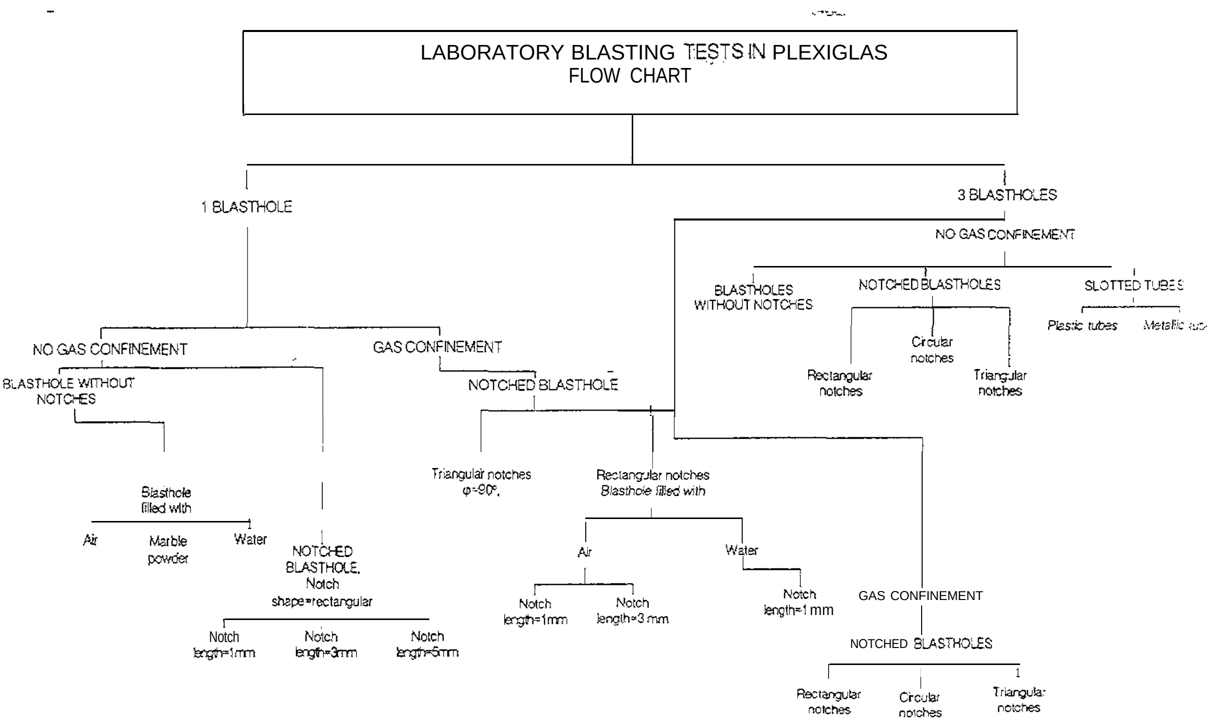


Figure 10. Flow chart of laboratory blasting tests using plexiglas models.

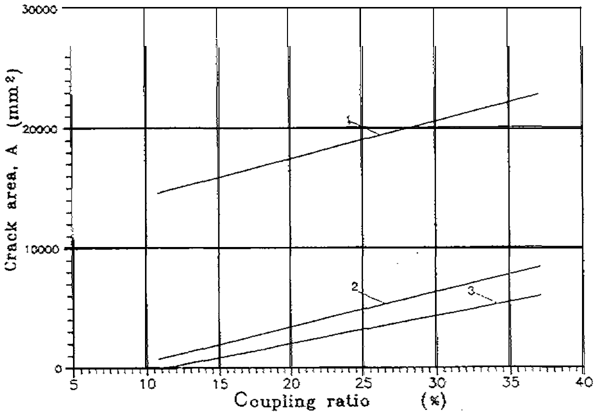


Figure 11. Comparison of producing crack area in single hole plexiglas specimens:
1: Blasthole filled with water
2: Blasthole filled with marble powder
3. Blasthole open to the air.

importance in fracturing of rocks by blasting. On the other hand there is not an effective way (material and process) up to now for stemming of the blastholes without a negative economic and time impact on the process of rock fracturing by blasting.

The presence of the notches at the blasthole wall affects the final effective crack length (50-80 % increase of final crack length relative to the un-notched holes), however, it does not affect the degree of undesired damage around the hole in comparison to un-notched holes.

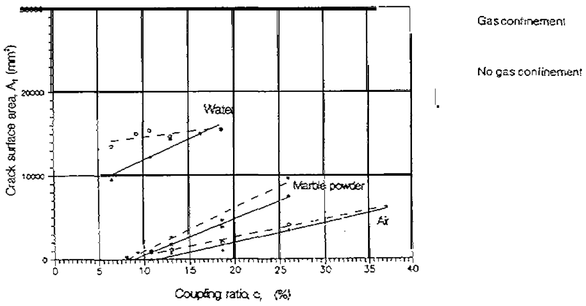


Figure 12. Effect of coupling ratio and of filling material (air, marble powder, water) in the crack surface area produced in the blasthole wall under gas confinement and unconfined conditions.

Notches characterized by the same length but with different shapes (rectangular, triangular, semi-circular) produce approximateiy the same final effective crack lengths.

As it was found both numerically and experimentally, the initial notch size does not affect the final crack lengths due to blasting of single holes without stemming (gas confinement); see Figs. 14 and 15.

in gas confinement conditions, both the effective crack length and peripheral damage

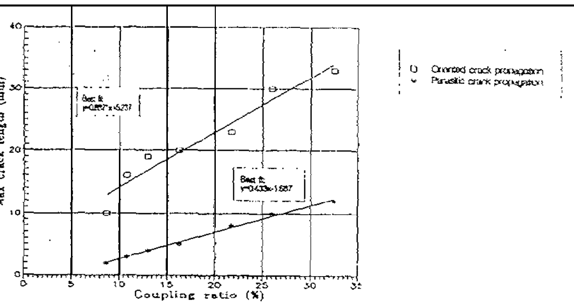


Figure 13. Influence of coupling ratio 'in the oriented and parasitic crack propagation in plexiglas models; Notch length = 3 mm; No gas confinement.

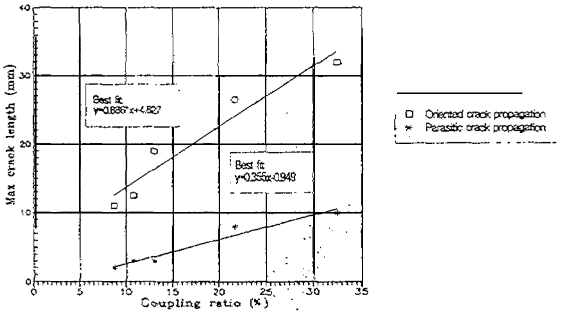


Figure 14. Influence of coupling ratio in the oriented and parasitic crack propagation in plexiglas models. Notch length = 1 mm; No gas confinement.

increase as compared to unconfined holes (without notches or slotted tubes). In the case of notched blastholes, gas confinement increases only the effective cracks while peripheral damage is the same as in the un-notched blastholes with no gas confinement.

- The employment of either plastic or metallic slotted tubes gives similar results to those produced by notching. More specifically, the use of metallic tubes may reduce the peripheral damage to zero or to increase it dramatically. This fact depends mainly on the ratio D/D_T, where D= Blasthole diameter and D_T =tube diameter, for all the other parameters remaining the same.
- The contribution of the shock wave to fracturing in marble appears to be lesser as compared to plexiglas fracturing. in general, in unconfined conditions no visible fracturing of marble was observed in specimens of 20 mm thickness. However, it is expected that the increase of specimen thickness will lead to an increase of marble fracturing when all the other conditions remain the same.
- The employment of bronze and plastic slotted tubes in marble was effective for the directed crack propagation along the blastholes plane. On the other hand, the notches were not found to be as effective as slotted tubes, especially in low coupling ratios (i.e. D_e/D = 0.15).

SMALL SCALE FIELD TESTS IN GRANITE

in order to obtain data on the influence of the blasting parameters (blasthole spacing, coupling ratio and type and characteristics of the explosive charges), a good number of different tests in granite at a mesoscale were performed,

The holes were drilled at different orientations with respect to the preferential fracture or weakness planes. Commercial blocks (about 7 m^3) were used. Several rows of holes were drilled, with different spacings.

The variables studied were: explosive charge per unit length of blasthole and per unit area of new surface, spacing between blastholes, coupling material and geometric placing of the charges. The following types of explosive were tested:

- Detonating cord 3 g/m.
- Detonating cord 6 g/m.
- Detonating cord 12 g/m.
- ANFO deck charges
- Low energy explosive. A newly formulated NG-based, low energy, low brisance explosive ("EPN") was manufactured for this work. EPN charges were 11 mm diameter, 1 m length rigid tubes filled with explosive. They were primed using electric caps.

Explosive to rock coupling was either air (i.e., uncoupled) or water. When ANFO charges were used, an air deck was placed between the explosive and the stemming. In some of the blasts, when water was used to couple the charges, a coloring agent was added in order to identify the direction of propagation of the fractures.

All the tests consisted in progressively varying each of the parameters, evacuating the results obtained in each shot in order to determine the optimum combination of the design parameters.

Results are summarized in Figs. 15 and 16. The following conclusions can be derived:

The use of water as filling substance allows larger blasthole spacings to obtain a specific quality of cut. By the same token, smaller charges (e.g. 6 g/m instead of 12 g/m detonating cord) can be used when water is present.

When air is used as "coupling" material (i.e., no filling is present inside the borehole), a higher charge of explosive is required to produce the cutting. This leads to a higher degree of fracturing around the blastholes, not only in the direction of the boreholes' line, but in other radial directions. As a result, a higher amount of material is lost. In granites, it is advisable to use low charges (e.g. 6 g/m detonating cord), with water inside the borehole, than high charges (e.g. 12 g/m detonating cord) without filling.

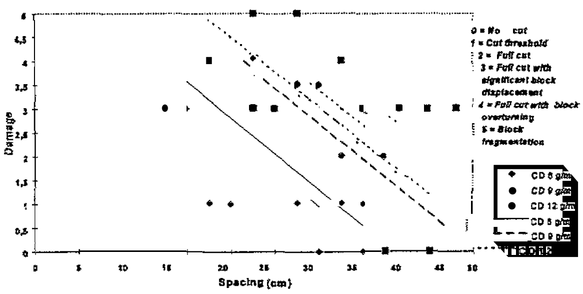


Figure 15. Relationship between damage to the rock and spacing.

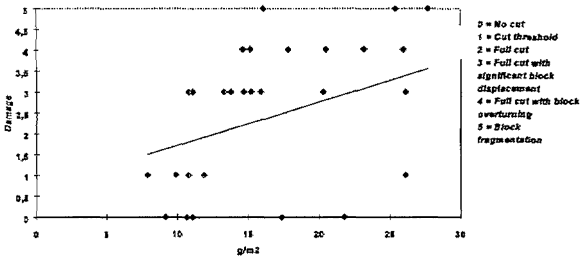


Figure 16. Relationship between damage and specific charge per unit surface.

- cutting along preferential (weakness) directions enables wider blasthole spacings -for a given charge- or smaller charges -for a given blasthole spacing-. The increase in spacing allowed when blasting along the weakness directions is of the same order as the reduction in compressive strength of the granite along those directions with respect to perpendicular ones. The same is true whenrefering to cutting in granites of different strength.
- The effect of dummy (uncharged] holes between charged holes has also been studied: more uniform cuts are normally observed with dummy holes.

[n what regards EPN, tests with this explosive proved the following:

- Shock energy transmission to the rock was by far very high, resulting in an excessive fracturing of the rock. This was particularly apparent when water was used as filling material. While brisance of the explosive was brought to a minimum (V.O. D. below 2000 m/s vs. more than 7000 m/s for PETN), coupling ratio was higher (7% for 6 g/m detonating cord vs. 32% for EPN tubes), this resulting in severe damage to the rock.
- Priming of the explosive tubes, either with a detonator or with detonating cord was arduous. Further development should be needed to improve this feature.
- For charges of great length, a male-female plugging system would help.
- EPN is highly hygroscopic, this property resulting in a certain probability of malfunction after lengthy storages. A certain degree of water resistance of the explosive pipes proved necessary.
- Larger borehole diameters (probably above 50 mm) should be used, so that the coupling ratio, which adversely affects the smooth blasting, is reduced.

The use of black powder in ornamental stone quarries is complementary -as bottom charge-to the detonating cord. The main effect of black powder is to open the rock joints to fracture; it has also an important heaving action, to separate the block from the rest of the rock mass or from the primary block.

The use of black powder shows two main problems: loss of time in preparation, and risk of breakage due to stresses during loading, resulting in a leakage of powder, which consequently becomes wet (as water is customary used as coupling material between the detonating cord and the borehole wall) and losing efficiency.

Hence, charges of black powder were designed and prepared to obtain a safer and more efficient use with detonating cord, avoiding the inconveniences mentioned. Black powder is placed inside rigid plastic pipes, 11 mm diameter, 50 cm long, each one containing 130 g of black powder approximately; the tubes are sealed in both ends, so that they are waterproof; detonating cord (usually 6 g/m) is fixed along the pipe by means of adhesive tape,

Charges of black powder prepared this way were tested for feasibility of use. Conclusions from the tests were the following:

- Cartridging provides some water resistance to black powder, preventing it from wetting.
- Decking of the charge allows placing it at the desired depths, avoiding underisable charge concentrations.
- Gas pressure is uniformly distributed along the blasthole, instead of being concentrated at the bottom.
- Flexible powder factor is enabled: it may be easily varied from hole to hole, depending on the local need of explosive strength.

LARGE SCALE TESTS

The more promising techniques pointed out in the preceding sections were tested in actual large scale blasts at different quarry sites.

a) Black powder decking in granite

In the stage of subdivision of primary blocks into slices, drilling and blasting is extensively used in quarries of granite.. The cutting procedure consists of drilling 32 mm nominal diameter holes, 30 cm apart, with lengths alternatively one and three meter less than the height of the block (usually in the vicinity of 10 m); the holes are, alternatively, about 6 and 8 meter long. Each of the boreholes is loaded with a charge of about 1 00 g of black powder, primed with 6 g/m detonating cord; drill cuttings are used to stem the black powder in the bottom of the hole; this stemming prevents the water filling of the hole from fully wetting the black powder.

Good enough cuts are obtained with this technique, but improvements were seen necessary and possible, as:

Charging is time consuming

When attempts have been made to increase borehole spacing, and larger charges of black powder are used, energy concentration in the bottom of the hole is also increased, thereby increasing the undesired craking

Cuts are of good quality, but the displacement at the splitting line is small (generally below 4 cm). This brings about the need of additional drilling and blasting of short length boreholes, in order to widen that separation (to a minimum of 11 cm), so that the edge of the pusher arm can be inserted, to overthrow the slice. This slows a great deal the process, and, at the same time, reduces the amount of valuable rock.

[n order to overcome this difficulty, an increase in the charge was apparently needed, whereas additional tincturing was to be avoided (that would be the case if the charge remained concentrated). In order to provide a more uniform application of the pressure, a decking of the charge along the borehole was used. This was done using the cartridges of black powder.

Decked charges of two cartridges of black powder per hole were tested. The cartridges were tied to the downhole line of detonating cord (6 g/m) using adhesive tape.

Six blastings were conducted in cutting slices ranging from 6,50 to 10,80 m long (face), 7 to 9,25 m high and 3,20 m thick.

Horizontal detachment of the primary block is done by means of a large diameter borehole (90 mm) loaded with black powder in the bottom. This is enough to make the horizontal cut, as the weakness plane is horizontal. As a consequence of using for this blast a high charge concentration in the bottom, detachment in this area is more apparent, which results in easier secondary cuts: In the primary block shown in Fig. 1, secondary cut #4 is easier than #1.

Fig. 18 shows the influence of the amount of black powder per unit surface on the separation of the block. Conclusions listed in the preceding section were confirmed. Besides, the following should be remarked:

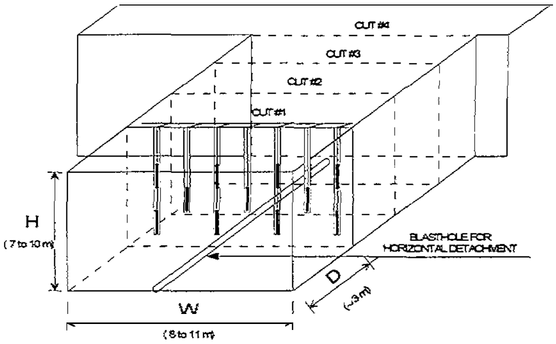


Figure 17. Cutting of slices using decked charges of black powder.

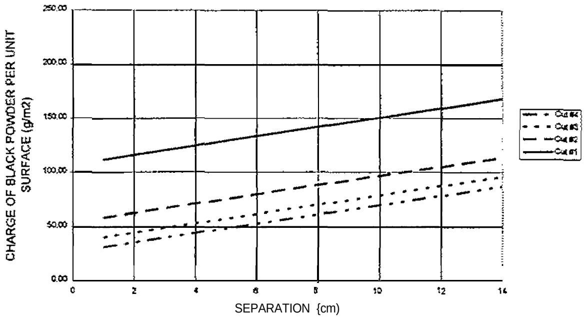


Figure 18. Separation of the block at the cutting line as a function of the charge of black powder and the position of the cut.

- Time saving: Loading and priming is done fast, as no on-site cardridging operation is needed.
- Cuts of better quality are obtained, probably due to the absence of charge concentration in the bottom, resulting in a more uniform pressure along the borehole.
- Individualized loading pattern of the boreholes, depending on their position in the blasting line, is allowed.
- Favorable acceptance of the quarrimen.

b} Blasting optimization in granite using notched holes

Several tests were carried out in granite quarries in Bustarviejo (Madrid) to study which would be the optimum design for cut blasting with notched boreholes. The parameters used in the study were the spacing between blastholes and the charge concentration, in order to find the most appropriate combination.

Lines of blastholes were drilled in granite blocks, of size ranging from 4 to 5 m^3; uniaxial compressive strength of the granite was 120 MPa. Notches 3 mm long were made with a drill steel driven by a drill hammer whose rotary device had been disabled. Rows of 28-30 mm diameter holes were loaded with a bottom charge of black powder and detonating cord. Boreholes spacing varied from 0.4 to 0.7 m; powder charge and cord weight were varied in the tests. Borehole filling was water in all cases.

The spacing between boreholes was varying in the different tests from 0,4 m to 0,7 m. Four tests were made, with several rows blasted in each test.

Fig. 19 shows the maximum allowable spacings as a function of detonating cord weight; results for cylindrical holes have been included for comparison. Spacing when using water coupling may be increased, for a given cord weight, to more than double as compared to that for an uncoupled charge. The use of notches, in turn, further increases the spacing by some 15 cm.

Decoupled borehole pressure required to get an efficient cut, for a given borehole spacing, is shown in Fig. 20, for both cylindrical and notched holes. This pressures are computed from the expresion (Calder and Bauer, 1983):

$$S = D\,(PB_e + T) / T$$

S being the maximum blasthole spacing for cut, D diameter, PB_e decoupled borehole pressure and T tensile strength. It is apparent that borehole pressure required using notches is about 30% lower than that required with cylindrical holes. There is, naturally, a minimum pressure required to produce the cut, this pressure being the critical pressure to initiate cracks.

Conclusions regarding tests with notched blastholes in granite can be summarized as follows:

Hole spacing can be increased by 25 to 40 percent.

Reduction in borehole pressure needed for the cut. This reduction in borehole pressure can be achieved by reducing the column charge to 1/3 of what is used with cylindrical holes. Hence, smaller charge concentrations could be used to propagate the fracture.

Excellent hole-to-hole fracturing was obtained and very little parasitic fracturing in other directions was observed. Consequently, rock waste is reduced.

Notched drilling increases by 20 to 30 percent the unit drilling cost as compared to cylindrical drilling.

Notches bring their full efficiency when they are all drilled in one plane. Deviations from this situation (customary, when made by hand) result in a drastic reduction of their benefit. Improvements of notches drilling equipment would certainly widen the use of notched holes, so far relatively restricted.

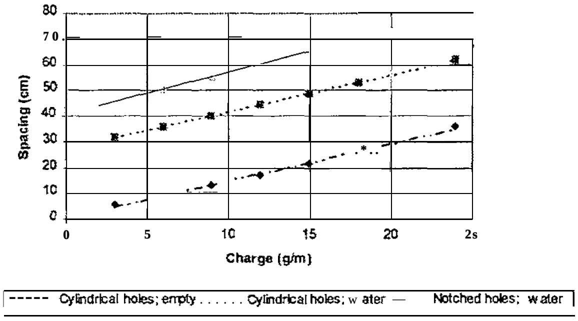


Figure 19. Charge vs. maximum spacing for the different tests.

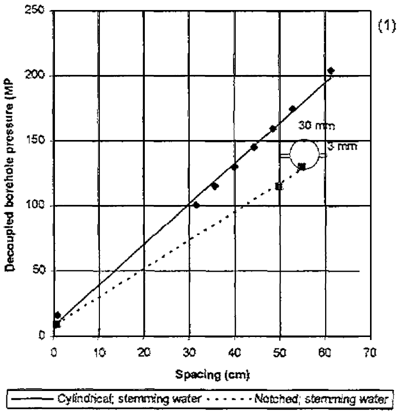


Figure 20. Spacings vs. decoupled borehole pressure. (1) This point may not correspond to a maximum blasthole spacing tests at wider spacings were not performed. Hence, pressure may be lower than as defined by this point.

c) Improved splitting technique for secondary blasting in marble

As the primary large marble blocks, which usually exceed 120 m^3 in size, are quarried at the bench using the diamond saw technique and that of drill and blast with black powder primed with detonating cord, fall down they break into smaller irregular boulders (blocks) due to the presence of fractures, joints and faults. Such irregular boulders or blocks must then be squared in blocks of appropriate marketable sizes. Squaring under the given structural features of the Dionyssos marble deposit yields an average recovery of about 12% of marketable blocks.

This secondary operation takes places in general by using three different techniques in order to square the irregular blocks:

- By applying the traditional and well known technique of drill and blast using decoupled linear charges of standard type detonating cord of 12 g/m charge in nominal 32 mm diameter blastholes. Drilling of such blastholes costs 1.1 to 1.7 ECU per meter and 8-9 blastholes are needed to produce one square meter of finished marble surface.

- By very dense drilling of holes with spacings as little as 3-10 cm followed by wedging (Fig. 21).
- In certain quarries the diamond saw technique is used which, however, for squaring small size blocks turns to be very costly and long.

Considering the high costs involved in squaring irregular blocks in order to produce a marketable product and the fact that squaring using the diamond saw technique is a very costly operation, an attempt was made to reduce this cost item. It is estimated that a reduction in drilling by 30% will reduce the cost per m^2 of the cutting surface by 5-8 ECU.

Extensive experimental field tests were carried out in Dionyssos, Naxos and Volakas quarries in order to develop an improved detonating cord technique during the processes of marble extraction from the bench site and squaring during the secondary stage. A detachable notching tool and a drill rod (with side-on flushing holes) were designed and constructed. Five different versions of the notching tool were tried; Fig. 22 shows these. These notching tools were effective for drilling diametrical triangle notches of 3-4 mm in length.

Field tests were carried out first in Dionyssos quarry. Blastholes were drilled perpendicular to the bedding plane, in directions F-F (zox) and T-T (zoy) (see Fig.21). Only a single test was carried out with the blastholes drilled parallel to bedding. Five different methods were tried in order to cut the marble blocks along the desired plane:

a) Use of standard detonating cord of 12 g/m.

b) Use of a combination of slotted plastic (PVC) tubes and detonating cord.

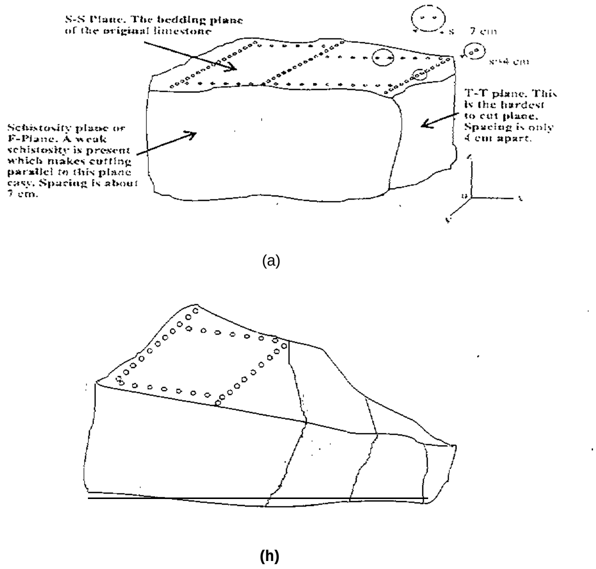
c} Use of notches only.

d) Use of a combination of notches and standard detonating cord.

e) Use of black powder combined with detonating cord of 12 g/m.

All blasting tests in which detonating cord was used were carried out with constant coupling ratio of 9%. The blasthole diameter was in all cases between 34-35 mm and the detonating cord used was of the standard type of 12 g/m having an effective explosive (PETN) diameter of 3 mm. The main conclusions drawn from these tests are:

- The use of detonating cord creates a damage zone (as measured with the projected crack length in the perpendicular to the cutting plane direction), with crack lengths varying from 3 to 7.5 cm depending on projected plane (this reduces the marketable size of the block and should be as small as possible}. Maximum spacing for achieving clean splitting along the F-plane is 14 cm while in the T-plane is 8.5 cm.



(a)

(h)

Figure 21. **(a)** Splitting of a primary **block into smaller blocks. (b) Squaring of an irregular boulder into a block. (Weak bedding and weak schistosity are only present in Dionyssos marble),**

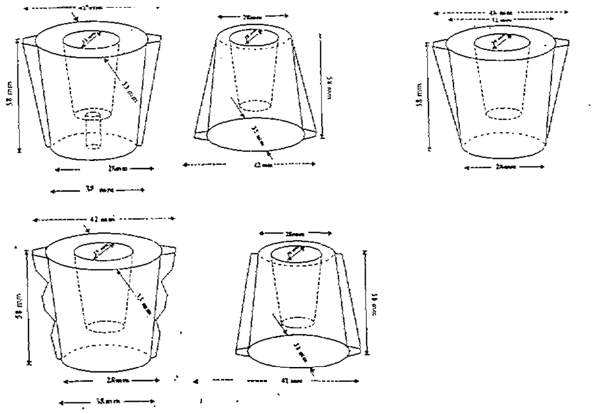


Figure 22. Notching tools.

The use of slotted plastic tubes combined with detonating cord is effective for cutting in the desired plane, but causes wall damage to the splitting plane.

Using only notched drillholes along the F-F plane (zoy), clean splitting was achieved with spacing up to 17 cm with the assistance of a one mechanical wedge pushed in one drillhole. No damage effect was recorded.

The use of notched blastholes combined with detonating cord is effective for cutting the marble block along both the T-plane (zoy) and F-plane (zox). For cutting along the F-plane (minor schistosity plane), an increase of spacing from 14 cm to 25 cm was observed while the damage effect remained the same. For cutting along the T-plane (the most difficult), spacing was increased from 8.5 cm to 13 cm, while the damage effect was about the same (6.5 -7 cm).

The use of combination of black powder and detonating cord causes wall damage perpendicular to the splitting plane {5.5 cm).

- The notch in a drillhole causes crack propagation in the desired direction with length of 6 cm.
- When cutting along the T-plane using notched drillholes with spacing 9 cm the irregularity of the cutting surface obtained is commercially acceptable.

Field tests were also carried out in large marble blocks ranging in volume from 1 to 4 m^3 in Volakas quarry. Due to the high metamorphism of the Volakas marble (dolomitic marble), no bedding or any schistosity are visible. It is assumed, therefore, that no anisotropy effects should be considered. Taking into consideration the experience gained from field tests in Dionyssos quarry, methods a), c) and d) were used in order to cut the marble block along the desired plane.

The main conclusions drawn from these tests are:

The maximum spacing between blastholes (edge to edge) for achieving clean splitting of the block using a single line of standard type detonating cord was 15,5 cm and 14 cm for the T-T plane and the F-F plane respectively. No damage zone due to blasting was recorded. The absence of recording any damage zone even when using penetrants can be attributed to the stress-strain diagram of the Volakas marble which exhibits high elastic strains at low stresses and a high modulus of elasticity.

The use of notched drillholes in combination with 3 mechanical wedges pushed into 3 drillholes is effective for cutting the marble block with spacings up to 33 cm between the drillholes.

The use of a combination of detonating cord and notched blastholes is effective for cutting the marble block with maximum spacing of 20 cm, while no damage effect was observed after the examination using penetrants.

The notch in a drillhole causes a crack propagation in the desired direction with length of 5.5 cm.

A relationship between spacing of the drillholes and the roughness profile of the splitting plane seems to exist. As the spacing increases, the surface roughness of the splitting plane increases also.

Field tests were also carried out in blocks ranging in volume from 1 to 3 m^3 in Naxos quarry. No bedding or any schistosity are visible in this marble. Methods a), c) and d) were also used in order to cut the marble block along the desired plane.

The main conclusions drawn from these tests are:

The use of detonating cord creates a damage zone (projected crack length in a direction perpendicular to the cutting plane), with crack lengths between 5 to 8 cm. This damage effect does not depend on the orientation of recording them.

- Maximum spacing for clear splitting using only detonating cord 12g/m is 15 cm, and it does not depend on the cutting direction (xoz or yoz) while for splitting in the S-plane was 20 cm.
- The use of notched drillholes is effective for splitting the marble block in the desired plane. Maximum spacing for splitting was 20 cm. Three wedges were used.
- The irregularity of the splitting surface increases as the spacing between the drillholes increases. This irregularity is critical for the commercial acceptance of the marble block.
- The use of notched blastholes does not affect the spacing between the blastholes for un-confined blast conditions.
- The use of a drill-bit of 32 mm nominal diameter, creates a drill hole of 35-36 mm diameter in Naxos marble, while in the two other quarries the diameter of the holes was 33-34 mm by using the same drill-bits. This is due to the bigger grain size of Naxos marble (3 mm) to the grain size of Volakas marble (0.4 mm) and Dionyssos marble (<1.0 mm). Because of this the length of the notch that was created with the use of the notching tool was 1-2 mm smaller.

PRACTICAL ASPECTS

a) Blasting parameters in granite with detonating cord

Precise indications of maximum allowable borehole spacing for 32 mm diameter holes in granites Blanco Castilla and Blanco Berrocal (see Table 1) are given in Fig. 19. In all cases, a bottom charge of approximately 100 g black powder must be used. Spacings given in Fig. 19 are for cutting planes (vertical) perpendicular to the weakness (horizontal) planes. Detachment in the horizontal plane may be done with a single large diameter (90 mm) borehole, loaded with a bottom charge of 7,5 kg of black powder.

It is to be noted that the notches bring their full efficiency when all are drilled in the splitting plane. Deviations from this situation may result in a drastic reduction of their benefit. Good alignment may need two people: one of them for guiding the hammer, and the other the drill steel: the additional labour cost is one of the major disadvantages of this technique, despite its very good results.

In the best case, notched drilling may increase by 20 to 30 percent the unit drilling cost, while the drilling length may be reduced (as the spacing is increased) by 25 to 40 percent.

b} Blasting parameters in granite with decked charges of black powder

Cutting of large slices from primary blocks maybe done by drilling 32 mm nominal diameter holes in succesive lines, with a spacing of 30 cm. Holes may be drilled to a length, alternately, of approximately 1 and 3 m less than the bench height, in order to prevent damage of the rock below the block. The block has been previously cut in the horizontal plane by a lifter blasthole. Short holes should be loaded with one cartridge in the bottom, and long ones with two cartridges, one in the bottom and a second one about 4 m from the collar (slightly above half depth of the borehole). In difficult cuts - front cuts, closer to the face, where horizontal detachment is not so neat- it may be advisable to load two cartridges in every hole.

Slices cut this way must be overturned by a pushing arm mounted on a loader. It is important, to improve the operation, that the edge of the arm can be inserted within the gap distance at the cutting line. Should this not be possible (the pushing arm edge is 4 cm wide), auxiliary holes of short length must be drilled and blasted, with a consequent slowing of the operation. Blasting of decked charges allows a higher charge in the blastholes, with a better heaving action and displacement, without bringing on an underisable charge concentration.

c) Drilling of notched holes

Manual drilling hammers are most often used to make notches. This system makes it difficult to align them perfectly in acmrdance with the direction of the cut.

Attention has been paid to the improvement of notches-making by mechanical means. A prototype of drill-and-notch borer ("block cutter") has been deviced. Component features and suitable working outlines are described.

One or more drill hammers, working on percussion only, are needed. Either if the rotation mechanism is a rifle bar or a ratchet wheel, it is possible to disable the rotation movement by simply removing the pawls.

In what respects notching bits, it is possible to make notches 3 mm long using Seriers 11 integral drill rods for drilling and Series 12 for notching, as the difference in bit diameter is 6 mm. This way, special drilling accessories are not needed. The disadvantage of this notching is that the notch may not be sharp enough, in order to direct the crack in the desired direction.

An adaptation of a conventional twin-hammer drilling system mounted on tracks is easily done: one of the hammers works on rotopercussion and the other on percussion only. The air circuit must have a pressure regulator, so that the power in the percussion hammer is lower than that in the rotopercussion one, in order to provide even penetration rates in both hammers: Notches, having a much smaller transverse surface than the boreholes, need a lower power to be drilled. Some tests must be done in the beginning of the work, with different air pressures (actuating on the pressure regulator) in order to determine the pressure that gives the same penetration rate in both hammers. This position would be kept until variations in the rock advise to change it.

Considering a block to be cut, and having the equipment on the working platform, and the tracks laid out, the working procedure would be as described in Fig. 23. Hammer 1 in the figure is equipped with series 12 drill rods, while hammer 2 with series 11.

A limiting feature of the equipment is the maximum distance of the hammers in the frame, as this is the maximum spacing allowed for the boreholes. A frame with four hammers can also be used, two of those working on percussion and the other two on rotopercussion. This needs a rather large supporting frame, at least three times the borehole spacing. Fig. 24 shows a sketch of such device (a two-hammer device would look similar, with two hammers in the frame}.

Another variant of the "block cutter" is one with two independent frames, one of them conventional, with the desired number of hammers, and the other *one* with percussive hammers. Both frames would

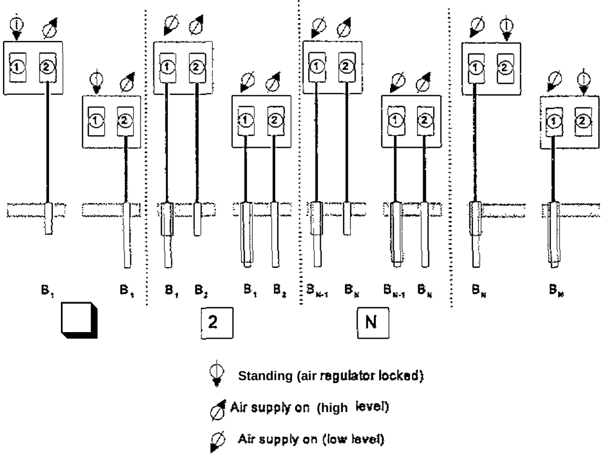
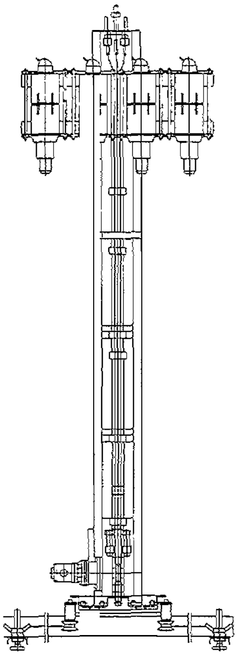


Figure 23. Combined work cycle with two hammers. ① Percussion (notching); ② Rotopercussion (drilling).



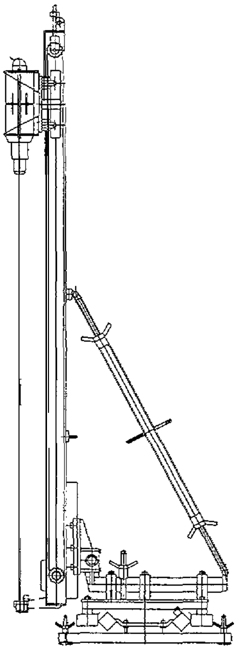


Figure 24. Four hammer “block cutter?

move on the same tracks. The first group would drill conventional holes at the desired spacing. The second group would follow, matching notches. As the penetration rate of the second group is higher than the first, the number of hammers in it can be smaller than that of the first group.

d) Marble block squaring using notched drillholes

Optimum spacing for squaring marble blocks using” notched drillholes in the” three-different marbles analyzed are given in Table 4.

The cost comparison between the improved squaring technique (notched drillholes) and the current applied technique is given in Table 5.

Table 4. Optimum spacings for squaring marble blocks using notched holes.

	BLASTHOLE SPACING (cm)		
SPLITTING PLANE (Fig. 21)	DIONYSSOS	VOLAKAS	NAXOS
S-plane	17	13	13
F-plane	14	13	12
T-plane	9	13	13

Notes on correct operating procedure:

The drillholes should be drilled at a single straightline row with no deviations if the notching is to be successful.

The orientation of notches should be aligned with the drillholes row if they are to work properly.

When notching, the drill steel axis has to coincide with the drillhole axis, otherwise the notches are not created properly and it would be difficult to bring the drill steel and the notching tool out of the drillhole.

The notching operation should be continuous.

If the splitting plane is next to the free surface of the irregular marble block, the spacing must be reduced by 20%, in order to prevent any free surface effect during the blasting stage (crack deviation from the desired splitting plane).

COMPUTER PROGRAM **FOR QUARRYING**

A computer code for the design of blasting operations, named “Blaster”, has been developed. The program is meant to help the quarry man in the design of his operation and the evaluation of costs.

Table 5. Cost comparison between notched holes squaring technique in marble and current technique.

Quarry	Dionyssos						Volakas		Naxos					
Splitting plane (Fig. 22)	s		F		T		AH		s		F		T	
C: Current method / N: Notched holes	C	N	C	N	C	N	C	N	C	N	C	N	C	N
Drillholes spacing (cm)	10	17	7	14	4	9	4	13	8	13	6	12	6	13
Drilled m per m² of split surface	8	5	10	6	14	8	14	6	9	7	11	7	11	7
Cost of single hammer machine in a retro arm (ECU/m²)	88	55	11	66	154	88	154	66	88	-	11	-	154	-
Drilling time (min/m²)	107	67	134	8	187	106	187	8	-	-	-	-	-	-
Cost of worker with drill hammer (ECU/m²)	136	85	17	102	238	136	238	102	153	119	187	119	187	119
Drilling time (min/m²)	254	16	318	19	445	255	445	19	254	223	35	223	35	223
Drilling reduction (%)		37		40		42		57		22		36		36
Cost reduction (%)		37		37		42		57		22		36		36

It became soon apparent that a program devoted exclusively to drilling and blasting in quarrying dimension stone would be of little use, as most quarries combine several techniques during the extraction process. For this reason, besides drilling and blasting, other techniques used in dimension stone quarrying are considered in Blaster: diamond wire, jet flame and wedges.

Software and hardware requirements are minimum, so that it can be used virtually in any type of personal computer. Input data required for the program are the following:

- Explosive: Name, VOD, density, price, weight per meter (detonating cord).
- Rock: Name, density, compressive and tensile stregths.

Data files are provided with properties of some explosives (black powder and detonating cords of several weights) and rocks (spanish granites and greek marbles).

- Dimensions of the block. Blaster requires the size of blocks in every cutting phase. At the first cutting, the initial dimension of the block to be extracted is defined by its height (ALT), width (ANC) and depth (FON). The second phase consists in subdividing the block into smaller ones with the same depth and height than the initial block. The ‘width of these blocks must be defined (EC). At the final phase, the user must define the height (E_c), depth (FOND) and width (ANCD) of the final block. Blaster gives the weight and number of total final blocks, and the geometrical recovery rate.

Calculations proceed through three phases, which correspond to the three stages of extraction and cutting process:

- Phase 1: Separation of the block from the rock mass.
- Phase 2: Cutting of slices from the primary block.
- Phase 3: Final cut to marketable blocks (typically of size around 5 to 10 *m’).*

Taking drilling and blasting technique as example -this being the main purpose of this work, and for the sake of concision-, calculations are summarized in Tables 6 (drilling) and 7 (blasting). Formulae for calculations are included in Tables 6 and 7; for detonating cord core diameter and blasthole spacing -notes (1) and (2) from Table 7-, the following expressions apply (meaning of symbols is given in Table 6}:

(1) For detonating cord, core diameter d (mm} is calculated by:

$$d = 2\sqrt{W/(\pi\rho_e)}$$

where W is the cord weight (g/m) and ρ_e is the PETN density; a typical value is 1,25 g/cm^3.

(2) Blasthole spacing is calculated as follows:

First, borehole pressure PB (MPa) is computed:

$$PB = 228\times10^{-6}\cdot\rho_e\cdot V_d{}^2/(1+0.8\rho_e)$$

For a decoupled shot, detonation gases will expand within the borehole to a pressure PB_e:

$$PB_e = K\cdot PB\cdot\left(\sqrt{c_l}\cdot d/D\right)^{2.4}$$

where K (coupling constant) accounts for an increase in wall pressure when materials other than air are filling the borehole. Finally, spacing E (cm) is calculated:

$$E = 0.1\cdot D\cdot(PB_e + K_w TS)/(K_w TS)$$

where TS is the tensile stregth (MPa) of the rock K_w is a “weakness” factor that accounts for preference directions along which cutting is favored. K_w is 0.8 for cuts along such directions, and unity for others.

Variables in the tables may be input (1) data, output (0), or read from data files (DB). In most cases, when input variables are required, default values supplied by the code may be used, if no guessing exists from the user.

CONCLUSIONS

The following conclusions should be highlighted:

Drilling and blasting methods are efficient in every cutting phases in medium and hard rock.

Decking of charges of black powder primed with low-weight detonating cord increases powder efficiency and produces better split surfaces. Charge concentrations are avoided.

Linear charges of high explosive should have a coupling ratio below 25-30% to avoid excessive parasitic cracking.

Water coupling allows low linear charges (e.g. 6 g/m) to be used in granite, while no such coupling is needed in marble.

Blasting of notched holes enables wider spacings (from 30 to over 100%, depending on the tensile strength of the rock). Notch size does not affect significantly the. notching effect.

Maximum allowable borehole spacings have been obtained for granite and marble splitting.

Careful drilling is of extreme importance, particularly when notching.

Borehole deviations and bad alignment of

Table 6. Calculations for drilling and blasting: drilling.

STAGE OF CUT: FIRST, SECONDARY, FINAL							
SYSTEM: DRILLING AND BLASTING							
PHASE: DRILLING							
ITEM	SYMBOL	I/O	UNIT	MAX.	MIN.	DEFAULT	FORMULA
Labor	MOP	I	u	3	1	2	
Drilling diameter	D	I	mm	51	26	36	
Length of charge to length of blastholes ratio	c_1	I		1		1	
Core or charge diameter	d	I/DB	mm	D		Formula	-1
V.O.D	V_d	DB	m/s				
Density of explosive	ρ_e	DB	g/cm^3				
coupling	K	I				Formula	For air K = I For sand K = 2,5 For water K = 5
Blastholes Spacing	E	O	cm			Formula	-2
Number of blastholes	Nb	O	u			Formula	PHASE 1: Cuts A & C Nb=1+100·FON/E Cut B Nb=1+100·ANC/E Lift up cut Nb=I +100·ANC/E PHASE 2: Single cut Nb=1+100·ANC/E PHASE 3: cut A Nb=1+100·FOND/E Cut B Nb=1+100·ANCD/E
Length of holes	L_b	0	m			Formula	PHASE 1: L_b = ALT PHASE 2: L_b = ALT-0,4 PHASE 3: L_b = ALT-0,4
Total length drilled	L_{tp}	O	m			Formula	$L_{tp} = L_b \times Nb$
Penetration rate	V_p	I	cm/min	200	10	100	
Penetration time	t_p	O	xxh yym			Formula	$t_p = (5.L_{tp}) / (3.V_p)$
Availability	P	I	%	100	50	75	
Drilling time	t_{tp}	O	xxh yym			Formula	$t_{tp} = t_p / \rho$
Fuel consumption	C	I	l/h	100	40	40	

Table 7. Calculations for drilling and blasting: blasting.

STAGE OF CUT: FIRST, SECONDARY, FINAL							
SYSTEM: DRILLING AND BLASTING							
PHASE: BLASTING							
ITEM	SYMBOL	I/O	UNIT	MAX.	MIN.	DEFAULT	FORMULA
Labor	MOC	I	u	3	1	2	
Detonating cord length	C_d	o	m			Formula	$C_d = [(c_1 \times L_b) + 0,015\ E] \times N b$
Black powder mass	Polv	I	kg	20	0	0	
Caps	Det	I	u			1	
Loading time	t_c	0	xxh yy m	-		Formula	t_e = 0,084. Nb

notches lead to poor splitting surfaces, parasitic cracking and smaller borehole spacings to ensure the cut.

- Quality and productive notching may only be made with drill-and-notch hammers (twin-hammer systems}. A preliminary design and working procedure for such equipment has been described.

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