IV. ULUSLARARASI TAŞ KONGRESİ

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BİLİMSEL ve TEKNİK DANIŞMA KURULU
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Underground Marble Exploitation - A Portuguese Case Study. Technical Aspects

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ABSTRACT

The underground ornamental rocks (dimension stones) exploitation has its specificities, according to the type of rock to be extracted and the geological characteristics of the rock mass. For economic and security reasons, the option to go for underground exploitation should be taken if an open pit is completely impossible.This study makes a brief historical introduction to the subject, presents the technical foundations that support it and presents the study of a case of application of underground marble exploitation in the anticlinal of Estremoz, Portugal.

Keywords: *Underground exploitation; Marbles; Portuguese quarry.*

1. INTRODUCTION

Main factors in favor of an underground exploitation of ornamental rock. Why underground exploitation?

- Rock with high economic value and excellent ornamental quality under a large sterile mass;
- Impossibility of quarry enlargement and removal of surface layers;
- Strong environmental pressure and if the exploitation develops in areas of great ecological value;
- Regions with accentuated reliefs;
- Regions with adverse weather conditions

What research is needed?

- Geological survey;
- Evaluation of structural characteristics of orebody;
- Evaluation of the geomechanical characteristics of the rocky massif;
- In-situ tension;
- Possible dimensions for the cavity;

- Yield;
- Continuity to three dimensions of the orebody.

Fundamental importance:

- Dimensioning of the pillars and their increase to the lower levels;
- Measurements of differential displacements with luminous or acoustic signals, extensiometric and geophysical measurements.

In short, as an underground ornamental rock exploitation can be considered definitive, the safety concerns to be had are very similar to those that occur in the construction of tunnels. So, the geomechanical characteristics of the rocky massifs allow us to define the method of underground disassemble that should guarantee the delicate balance of three fundamental factors for the success of an exploitation:

- Economic Factor;
- Reduction of fracturing induction as exploitation progresses;
- Ensure cavity stability during exploitation.

2. A BIT OF HISTORY

The pioneers of underground marble exploitation were the Egyptians, the Greeks and the Romans, in limestone masses with well-defined horizontal stratification, where they developed mining works in wells and galleries.

An example is the Jordan Valley quarry (Fig. 1), it was discovered by Prof. Adam Zertal and his team at the University of Haifa. It is located in the desert, north of Jericho, 10 meters below the surface. The cavity is about 0.4 hectares and the main chamber has 22 pillars where various symbols are engraved, including Byzantine crosses, a symbol of the zodiac and Roman numerals. An engraved pennant from the Roman legion indicates that this site was used by the Roman army. The cavity was excavated about 2,000 years ago and served as a great quarry during the Roman era. The quarry it worked for approximately 400 to 500 years.

Figure 1 – Jordan Valley quarry. Photo: University of Haifa.

The Pentelikon marble employed in the construction of the Parthenon, the Erechtheum, the Propylaea of the Acropolis, the Theseum, the temple of Olympus Zeusand other major works was the first marble to be mined from an underground quarry. In ancient Greece, the statuary marble of the Paros island was mined underground.

During Roman Empire, the limestone quarry, Aurisina, in the Karst region, near Trieste became famous. They are, now, working in an open pit. In fact, some marble-producing centers, currently exploited, began more than 2000 years ago. The Lunese marble was intensely extracted during the Roman Empire, in the governance of the emperors Augustus and Marcus Aurelius, there being vestiges of that exploitation in Carrara (Colonnata, old colony of slaves, Miseglia and Torano).

The Technique

The Romans learned and improved the extraction techniques invented by the Greeks and Egyptians.

In ancient Rome and ancient Greece, the cutting technique known as the "Roman Cut" was used both in the open pit and underground exploitation, based on the introduction of wet wedges of wood in the natural fissures of the stone. All work was manual with feature hammers, mallets, pickaxes and chisels. The cutters often used picks to make grooves and separate the blocks. Beyond wedges were also used wooden bars that, after immersion, exerted a lateral pressure which would separate the block (Fig. 2). This method was particularly simple, especially in quarries of stratified limestone, where the horizontal discontinuities made it easier to detach the blocks, being a natural factor that determined their dimensions.

Figure 2 –Ancient method of block separation. Image: LeenRitmeyer

Traces of Roman exploitation found in a marble quarry in Vila Viçosa (Fig. 3), Portugal and studied by students of the Geological Engineering at the University of Évora, proving the interest that portuguese marbles aroused, already in ancient Rome.

Figure 3 –Traces of Roman exploitation found in a marble quarry in Vila Viçosa.

The Underground Exploitation

In the region of Portoro, La Spezia, Italy, in antiquity, marble was excavated by using human strength. The dismantling operations consisted, initially, in the creation of a low tunnel to locate the deposit, through the use of the chisel and sledgehammer. After opening the tunnel was defined the width of the blocks by the execution of two lateral channels that enabled two men with a large, toothless tempered saw to make the lower and posterior cuts. The cutting action was aided by the introduction of water and siliceous sand. Removal of the block was done using wooden or iron wedges (Del Soldato and Pintus, 1985, *in* Guerreiro, 2000) (Fig. 4). The movement of the blocks was done with load animals and the progression was made on rolls of wood that were successively removed from the rear and placed at the front.

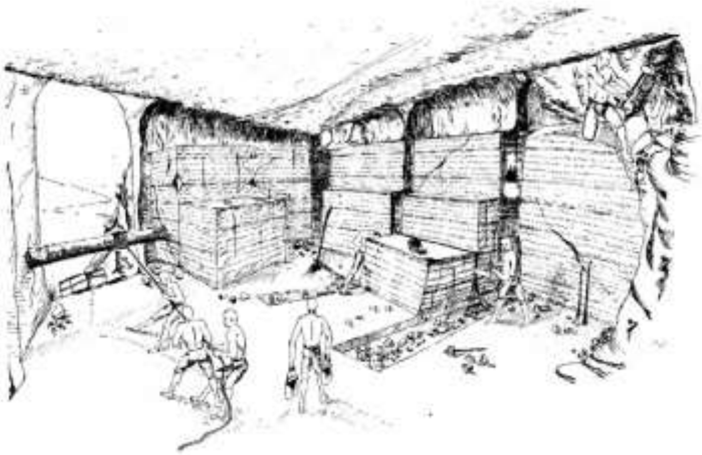

Figure 4 –Model of ancient underground exploration.Image: Del Soldato e Pintus, 1985 *in* Guerreiro, H. (2000).

The displacement of the block out of the cavity was made using gravity called Lizza in Carrara (Fig. 5), and the movement was controlled by men with ropes wrapped in wooden bars.

Figure 5 – A) Monument to the Cavatore, Colonnata, Carrara, Italy.
B) Traces of Lizza in Carrara.

At present the underground mining of ornamental rocks has been developed in Italy, Spain, Portugal, Croatia, Greece, France, Slovenia, Turkey and USA. The world's largest underground quarry is located in Vermont, USA (Vermont Marble Company) and has been in operation for over 200 years. It has 6 levels of extraction and the processing unit was assembled inside the quarry (http://www.vermontquarries.com/danby-quarry/).

Blocks Squaring

One of the older systems of stone sawing was painfully executed by two slaves, using sisal rope, sand and water.The same method has remained to this day with sisal being replaced with iron and devices having been created more effective than human effort.
The Hierapolis sawmill is believed to be a Roman water-powered stone sawmill invented by the Romans to cut stone using water, it was discovered at Hierapolis, Asia Minor (modern-day Turkey). Dating from the second half of the 3rd century AC, the sawmill is considered the earliest known machine to combine a crank with a connecting rod, although neither clear ancient scripts or engineering drawings were yet found to support this theory.

3. UNDERGROUND EXPLOITATION METHODS

Although there are many methods of underground exploration, particularly in the exploration of metallic ores, we'll consider only three types of traditional dismantle:

- Block Caving Stope
- Filling Methods Stope;
- Chambers and Pillars Stope.

In the underground exploitation of ornamental rocks, blocometry is a fundamental factor for the economic viability of the extractive unit, so the selection of the method is of crucial importance.So, the method of block caving is not advisable considering that it increases the fracture of the rocky mass, leading inevitably to the reduction of blocometry.The filling method does not appear to be favorable in most underground ornamental rocks due to technical issues of the development of the exploitation and due to relatively small areas, however, the use of this method is allowed in specific cases to reduce problems related to instability or abandonment of sites due to the exhaustion of the reserve.
In underground mining for ornamental rocks, the best method is the one of chambers and pillars (Fig. 6), this method is widespread throughout the world where natural pillars become support members, and containment ceilings. The projection of the location of these pillars, as well as their dimensioning, should be done taking into account locations with rock of lower ornamental quality and in the sense of reducing the possibility of induced fracturing due to the opening of the cavities.

The spatial distribution of the pillars may be irregular due to the heterogeneity of the rock formation.

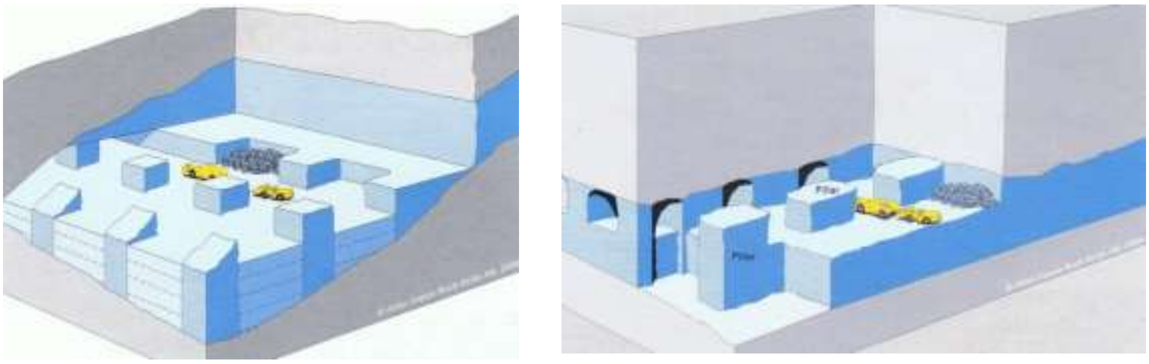

Fig. 6 – Chambers and pillars in underground mining exploitation.Adapted from Atlas Copco; Mining Methods, Case Study.

Dimensioning of the Pillars

The design of the stopes can be done through the theory of the influence area or numerical analysis methods, using software with finite element method and finite difference.

One of the most used methods for dimensioning chambers and columns is the tributary area (area of influence) (Fig. 7), which considers the pillar subject to vertical lithostatic tension corresponding to the area it supports. This method compares the tension applied to the pillar with its compressive strength, but it does not contemplate the orientation of the discontinuities that can change the stress distribution (Guerreiro, 2000).

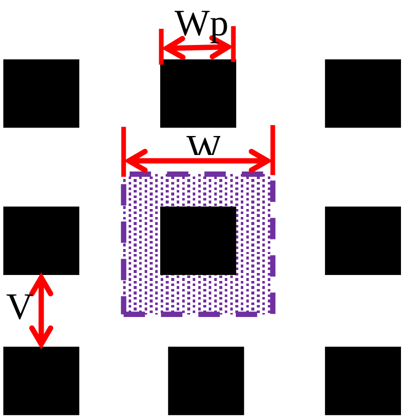

Fig. 7 – Influence area for dimensioning chambers and columns.

V – Chambers span; W – Width of total area; Wp – Width of pillar.

To calculate the span (V) it is suggested to use the following formula:

$$V_S = \sqrt{\frac{2a\sigma_t}{\left(\gamma + \frac{P}{a}\right)F_s}}$$

Vs – Safe span from the ceiling.

a – Coverage slab thickness.

σ_t– Tensile strength of the slab forming the ceiling.

F_s – Safety factor.

γ – Specific weight of the material.

P – External pressure due to air, water etc.

Safety factor - $F_S = \frac{\sigma_r}{\sigma_a}$

σ_r – Breaking strength; σ_a - Working tension or acting.

Another important factor is slenderness (Table 1).Slenderness - considering "Wp" the width of the pillar and "Hp" at a height, it is verified according to Salamon and Oravecz (1976) that:

• For constant "Wp", the resistance decreases with increasing height "Hp" (more slenderness);

• For constant "Hp", the resistance decreases with decreasing width"Wp" (more slenderness).

Table 1 - Values of uniaxial compression strength for portuguese marble.

Slenderness	Uniaxial CompressionResistance σ_c (MPa)
h/w = 2	69,6
h/w = 3	62,7
h/w = 4	57,8
h/w = 5	54,0

For pillars where Hp / Wp<3 weakening due to slenderness may be negligible (Fornaro and Bosticco, 1995a).

4. TEXUGO QUARRY – A CASE STUDY

The case study of the Texugo Quarry will be presented, which has a mixed exploitation, with an open pit and an underground. The quarry is located in the municipality of Vila Viçosa, Évora district, being part of the Captivate Area of Marble Exploitation of the Estremoz Anticline, Portugal.

The main marble extraction center in Portugal has about four hundred quarries, located in the region of Alentejo, at a distance of one hundred and fifty kilometers from the beautiful city of Lisbon and capital of Portugal, two hundred and seventy kilometers from the city of Oporto and from one of the best wines in the world, Port wine and one hundred and ninety kilometers from the beautiful beaches of the Algarve.

The marble zone belongs to a region with low relief, so underground mining does not seem to be the best option, however, there are some examples of this type of exploitation, when high quality marble is below a considerable thickness of another type of rock with no ornamental value.

The Texugo quarry is located in the municipality of Vila Viçosa, Évora district, being part of the area reserved for the exploitation of marbles of the Estremoz Anticlinal. Is located on the southwest flank of the Estremoz Anticline which is an elliptical-shaped geological structure, about 42 km long and 8 km wide, NW-SE orientation (Fig. 8).

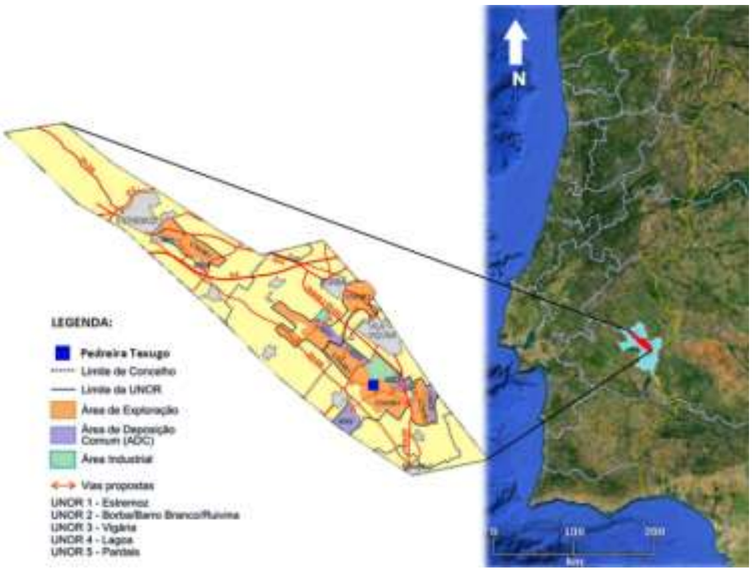

Fig. 8 –Location of Texugo quarry.

- In nineteen seventy-two it was started the exploitation in open pit with Bertos International company.

- In nineteen eighty-seven the quarry had two floors and was bought by the Lugramar, Lda company;

- In two thousand, underground exploitation began with the opening of two galleries at the same time on the sixth floor and a gallery on the fifth floor.

- Since that date the exploitation has a mixed character, developing simultaneously in underground and open pit.

- In twenty fifteen the quarry was bought by the Bloco B, Lda. Company.

- Nowadays, the exploitation continues to be of a mixed nature, developing in the open pit, by the method of right steps and underground, through the method of chambers and pillars. The lower quota of the open pit quarry corresponds to the tenth floor being sixty-five meters above the surface. The underground is currently seven floors and the lower level is seventy-one meters (Fig. 9).

Figure 9 – Texugo quarry.

Some Geotechnical Parameters

Ornamental zones were initially created based on the chromatic characteristics of the stone (Fig. 10).

Three zones with different geomechanical behavior were identified in geotechnical zoning (Table 2). For this zoning the following parameters were used:

-Geomechanical classification of Bieniwaski (RMR – Rock Mass Ratimg);

-Uniaxial compressive strength, where cylindrical test pieces are compressed parallel to their longitudinal axis;

-RQD(Rock Quality Designation); Determines the degree of fracturing of the massif.

-Discontinuities analysis (spacing, roughness and humidity).

From the various ornamental and geotechnical zones, the zones of the deposit were defined qualitatively (Fig. 11), from the point of view of underground exploitation.

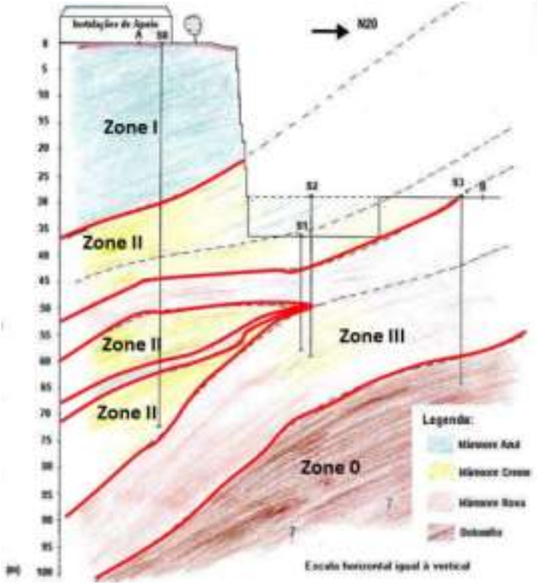

Fig. 10 – Ornamental zones; Texugo quarry (adapted fromCevalor, Lugramar; Plano de Lavra, 2001).

Zone 0 - Dolomite - No ornamental suitability.
Zone I – Blue Marble - Low or no ornamental suitability.
Zone II - Marble with some veins - Good ornamental suitability.
Zone III - Cream marble and pink marble with little or no veins - Very good ornamental suitability.

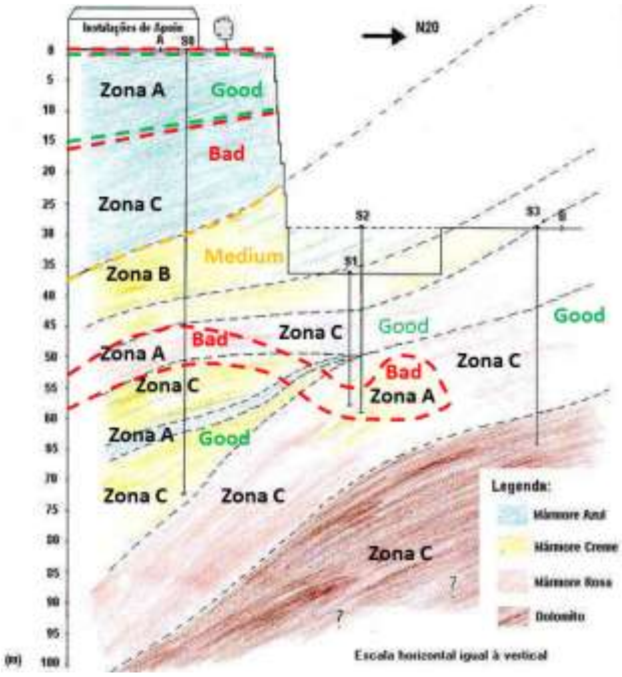

Figure 11 – Qualitative zones for underground exploitation.quarry (adapted from Cevalor, Lugramar; Plano de Lavra, 2001).

Table 2 – Geothecnical Zones; Texugo quarry(adapted from Cevalor, Lugramar; Plano de Lavra, 2001).

Geotechnical zone	Characteristics					Classification (based on the RMR value of the Bieniawski classification)
Zone A Rocky massif of medium quality	Very fractured blue marble					RMR = 42 Medium rocky massif
	σ_c= 64MPa	RQD 25-50%	Spacing 200-600mm	Slightly roughened and altered fractures	Presence of water in fractures	
	Clear marble with veins very fractured					RMR = 47 Medium rocky massif
	σ_c= 61MPa	RQD 25-50%	Spacing 200-600mm	Slightly roughened and slightly altered fractures	Moist fractures	
	Clear marble with little veins very fractured					RMR = 47 Medium rocky massif
	σ_c= 94MPa	RQD 25-50%	Spacing 200-600mm	Slightly roughened and slightly altered fractures	Moist fractures	
Zone B Rocky massif of medium to good quality	Clear marble with little veins, moderately fractured					RMR = 57 Medium rocky massif
	σ_c= 61MPa	RQD 50 - 75%	Spacing 0,6 - 2m	Slightly roughened and slightly altered fractures	Moist fractures	
Zone C Rocky massif of good quality	Blue marble, little fractured					RMR = 61 Solid rocky massif
	σ_c= 64MPa	RQD 75 - 90%	Spacing 0,6 - 2m	Slightly roughened and slightly altered fractures	Moist fractures	
	Clear marble with little veins and little fractured					RMR = 61 Solid rocky massif
	σ_c= 94MPa	RQD 75 - 90%	Spacing 0,6 - 2m	Slightly roughened and slightly altered fractures	Moist fractures	
	Dolomite					
	σ_c= 78MPa	RQD 75 - 90%	Spacing 0,6 - 2m	Slightly roughened and slightly altered fractures	Moist fractures	RMR = 64 Solid rocky massif

From tests carried out it was determined vertical tension σv = 1,34 MPa. The strength of the pillars should be seventy percent of the mean value minus the standard deviation of the compressive strength of the rock. For marble with veins it should be equal to = 37 MPa. Considering the size of the used diamond belt sawing machine that allows advancements of 6 m and heights of 4.5 m, a size of the spans of 12 m was started. Considering a safety factor greater or equal to five. A column width of 9m was calculated which leads to a recovery rate of eighty-two point five percent (82.5%). For the dimension of the chambers the theory of embedded beams was adopted. For spans of 12 m, the safety of the roof in relation to flexural phenomena is guaranteed, since there is a thickness of covering material that functions as a beam of more than 0,5 m (limit situation) for a tensile strength of four mega pascals. In the case of the Texugo Quarry there is a thickness of covering rock approximately twenty-five meters (25 m).

Gallery advancement

Traditionally the advance gallery is made using the decentered cross technique (Fig. 12), with the use of diamond belt sawing machine. First the horizontal cuts are realized, with two meters of depth and spacing of two and half meters between the lower and the intermediate cut and of one meter between this and the superior cut. Then the vertical cuts are made, with one meter between the left and the intermediate cuts and with five meters between this and the right cut. After the cuts have been made, blocks one, two, three and four are individualized, being attached to the rocky massif by the back. Blocks one and two are detached from the back by placing a small hydro bag (With the capacity to remove seventy-five tons) at the base of the second block, filling it with water until the release occurs. Removal of blocks one and two is done with a crawler excavator. Subsequently, the largest masses consisting of blocks three and four are cut with a diamond wire machine, being removed the same way. This completes a cycle of advancing a gallery.

Floor Lowering

After obtaining a large chamber with a correct distribution of the pillars, initially projected, we start the process of lowering the floor (Fig. 13). Four holes of six meters of length are executed, with a Drill Jumbo and with a bit of two hundred and twenty millimeters in diameter. Then two diagonal holes are drilled with the rotopercussive pneumatic drill, with a bit of ninety millimeters in diameter, from the top of one of the holes already executed until it intercepts the base of the opposite hole. In the following phase the widths of the slices with vertical holes are defined with light pneumatic hammers and diameter of thirty millimeters. The cuts with diamond wire machine are executed in the following order:

- Vertical cut realized in a traditional way with pulleys at the bottom of the hole with a diameter of two hundred millimeters and a driving pulley of the machine with a diameter of eight hundred millimeters due to the high peripheral speed observed in the smaller pulleys.;
- Diagonal cut;
- Slice cutting;
- Side cuts.

Is thus separated an upper wedge which is removed slice by slicewith the aid of a mobile crane, starting with the smaller slices.

Figure 12 –Gallery advancement made using the decentered cross technique. Original draws by Emanuel Branco.

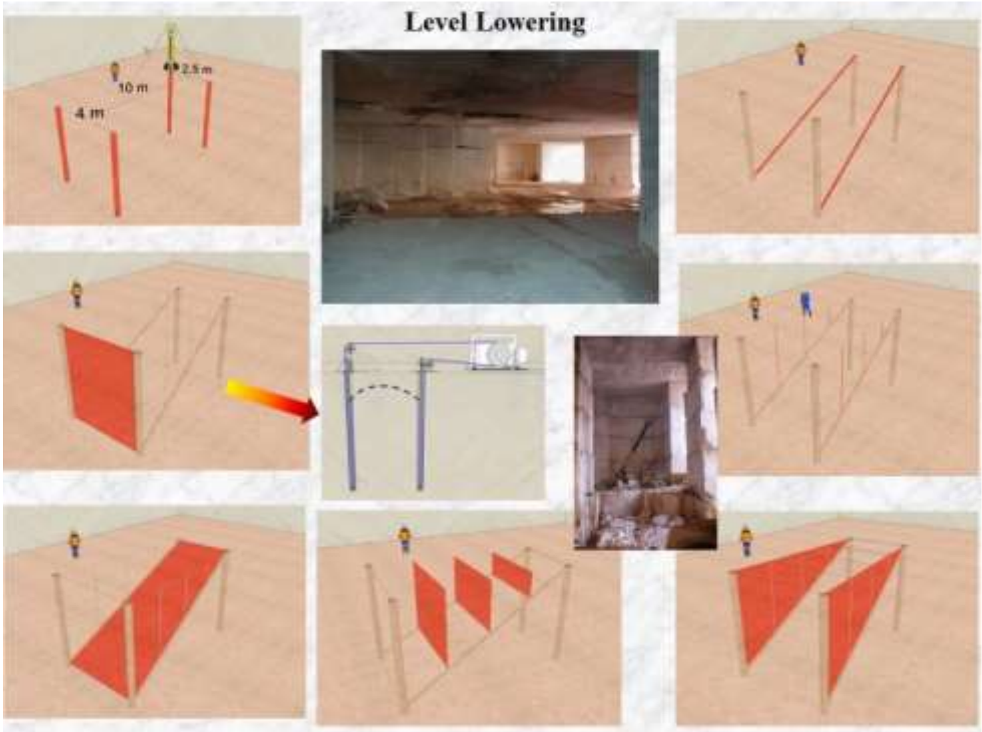

Figure 13 – Process of lowering the floor.Original draws by Emanuel Branco.

To detach and remove the lower wedge, the sequence of processes is similar (Fig. 14). However, before drilling the horizontal holes it is necessary to remove the wedge point for placement of the pneumatic drill.At the end we will have a floor lowering box, from which will develop channels and dismount on the bench by right steps, as it happens in open pit.

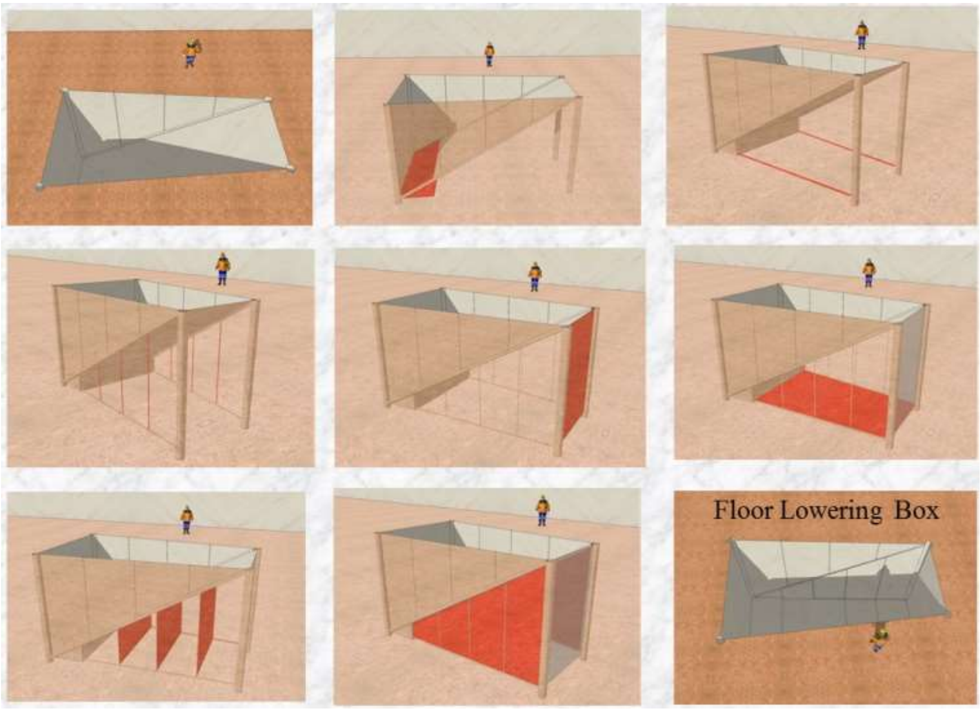

Figure 14– Detach and remove the lower wedge.Original draws by Emanuel Branco.

5. THE BIG QUESTION: WHICH IS THE BEST OPTION?

We have the same geological formation, with the same characteristics. On one hand the option of an underground exploitation in 2000 by the company Lugramar, on the other hand the option of an open pit exploitation by the company António Galego (Fig. 15).

Figure 15 – Underground versus open pit exploitation I.

The option of underground exploitation, at the end of nineteen years, left to support the ceilings, five pillars with the referred dimensions (Fig. 16) and a total of nineteen thousand, nine hundred and sixty-five cubic meters.Considering the average yield of the open pit exploitation of twenty-two percent, would be obtained four thousand, three hundred and ninety-two cubic meters of marketable stone.Considering the block's average value in the order of three hundred and twenty-five euros per cubic meter, a commercial value of a total mass of one million, four hundred twenty-seven thousand and four hundred euros would be obtained.However, since the current underground area is an area of very good quality, where pink and clear creams marbles prevail, obtaining an average of about forty percent of the yield, it is expected that, if the open pit exploitation had developed, the yield in this area would exceed twenty-two per cent.

Figure 16– Underground versus open pit exploitation II.

The António Galego Company opted to remove two hundred and fifty thousand cubic meters (250000 m^3) of sterile mass and black marbles of low value.In four years it has removed about thirty percent of the mass, remaining seventy percent that at the current rate of exploitation and adequate mining planning is expected to take nine to ten years until the entire top layer is removed. The zero level is constituted by the first six meters of thickness and had yield zero. The two and a half floors seven meters high each had yields of up to ten percent (Fig. 17).

Figure 17– Underground versus open pit exploitation III.

We finished, leaving the reader with the question suspended - what is the best option? Both are valid, however, before choosing any one of them, all the factors that have been analyzed throughout this text must be weighed in detail and never advance rashly forward. This is the only way to achieve profitable and sustainable exploitation.

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