Journal of Mining Science, Vol. 44, No. 1, 2008

PROCEDURES FOR GEOTECHNICAL CHARACTERIZATION AND ECONOMICAL FEASIBILITY STUDIES – APPLICATION TO AN UNDERGROUND MARBLE EXPLOITATION

M. Matilde Costa e Silva and P. Falcão Neves UDC 622.272.658

For marble underground excavation it is important to develop a collection of procedures, rules and models in order to collect information to build a database, making it usable and available to all users so that they can make decisions. The information must be based on technical and economic criteria, during the lifetime of the excavation and after the close down of the mining activities. The importance of geotechnical characterization in the economical evaluation of underground mining of dimension stone is so emphasized. A sensitivity analysis of the economic indicators with the variation of the geotechnical and ornamental parameters is performed. The results of an economic feasibility study of an underground exploitation of marble at Pardais, Vila Viçosa, are presented.

Geotechnics, economical feasibility, marble, quarry, management procedures

INTRODUCTION

In small areas inside a quarry, several geotechnical parameters change, sometimes apparently without rules. For example, even if mechanical characteristics are quite constants, with very small variations, the highly fracture density (that leads to a large quantity of different dimensions and forms of blocks) and the changes in colours both in matrix and veins are very frequent, being very difficult to get large stocks of marble with the same mechanical/commercial/aesthetic characteristics. As well known, the price of marble blocks is made accordingly to its geometry, size and especially its matrix colours and veins, among with other factors. It is very important to implement an interactive management information system for zoning rock masses, to map mechanical or structural parameters, recovery rate, changes in block dimension and colours, in actual and in future mining excavations areas.

The classification of potential risk (structural stability, affected production and commercial aspects) and management procedures presented in this paper will help decision makers to understand the uncertainty created by multiple combinations of variables resulting different scenarios [1].

The economic feasibility case study of a marble underground exploitation in Pardais, Vila Viçosa is presented. In order to perform such study, geological campaigns were made at the target area, allowing identification of density and natural direction of faults of the solid, as well as the zoning of the quality of the marble which could be extracted. The study of the geotechnical nature of the area was critical, since only the full knowledge of the geomechanical characteristics of the solid to be exploited allows the prediction of service behaviour, and thus, to adopt the adequate quarrying method and it's dimensioning and safety factors afterwards.

CEGEO Geotecnical Center, IST, Technical University of Lisbon, E-mail: matilde.horta@ist.utl.pt, pfalcaoneves@mail.ist.utl.pt, Lisbon, Portugal. Translated from Fiziko-Tekhnicheskie Problemy Razrabotki Poleznykh Iskopaemykh, No. 1, pp. 101-110, January-February, 2008. Original article submitted February 2, 2007.

1062-7391/08/4401-0092

MANAGEMENT PROCEDURES FOR AN UNDERGROUND EXCAVATION OF MARBLE

A marble underground exploitation project should be based in a significant range of geologic and structural conditions. In fact, a project of this kind will only be successful if good quality mineral resources are available to be exploited with benefit to the investor.

The interactive management information system (IMIS) will inform about potential risk (geotechnical, production and commercial factors variations); organise monitoring actions and make statistical analysis. This information is fundamental for the decision support system, helping engineering planning, using technical and economical criteria. In underground marble quarry this type of control is new. Even in surface quarrying the systematic technical-economical control is not yet a common tool. The success of any dimension stone company cannot be based in simple standard mining planning actions. The decisions have to consider not only structural and mechanical parameters but also market dependent factors (different clients need certain quantities and specifics types of marble in different times; which are not always available).

For the success of the management procedures of marble underground excavations it is essential to standardise the data monitoring collection and their subsequent results treatment, during not only the mining activities and also afterwards. In this way, the system could not be affected, even if the teamwork is changed, once the decisions should be based on clear, objective criteria and procedures. These are the reasons that make so important workers technical formation actions and the establishment of monitoring procedures manuals.

This interactive management information system (IMIS) will help zoning the rock mass in accordance with the potential instability (of the mass and also of the stope) and establish methodologies of diagnosis and maintenance techniques (for any structural anomaly). The risk detected must be described /quantified with procedures that makes possible that lead to the same actions, regardless the teamwork. The investigation/confirmation of the cause must lead to the same conclusions regardless the factor non-objectiveness. The same is applied to methods of diagnosis and maintenance works and in planning actions. All these components have to be related through a correlation matrix. Finally this methodology will allow the complete knowledge of the underground quarry potential risk in order to take supported decisions in real time. The management system has different moduli: database, monitoring system and decision support system.

To implement IMIS to marble underground excavations the first procedure is a Database generation with technical and commercial data from original project and reports that will define the reference situation. The execution of field forms, inputs to database, with geotechnical data (topographic, geological, geo-structural, geomechanical), commercial aspects (block dimension, matrix and vein colours) of the quarry and the stopes are extremely important to establish the differences and evolution of these parameters during mining activities. This information may also be available in graphical support (maps).

Monitoring forms with periodical information (systematic and special) are also important, being able to conduct future diagnosis to program maintenance works and repairs; to control the evolution of any commercial anomaly leading to necessary mining planning changes. This information allows parametric studies and the execution of extraction recovery mapping. Monitoring forms with detail description and measurements of specific parameters are created. Elaboration of a matrix with cause/consequence/potential risk, possible symptoms and signs easily detected in visual inspection or with other monitoring method are also generated.

These forms will be part of the procedures of monitoring manuals that have to be used during site visiting. The build up of a database for a decision support system is also considered, in such a way that when a potential risk is detected, during the monitoring work, it is automatically classified accordingly the urgent actuation and its importance to the stability of marble stopes or its impact in mining recovery or mining planning.

The Modulus Database will receive information data from the project and information obtained through field and monitoring forms. Table 1 shows an example of a typical field form where is made the input of topographic, geographic, geotechnical, block dimension, geological, hydrogeology, commercial and administrative data. Commercial data has information about matrix and vein colour, vein density, variations in colours inside a certain area, price/cubic meter, block dimension, among others.

With this routine procedure it's possible to zone geotechnical properties and commercial parameters allowing a continuous improvement of mining management and in the future engineering projects the use of this accumulated knowledge.

TABLE 1. Example of a Part of the Information in a Monitoring Form

Monitoring form (underground marble quarry)				
Type :periodical monitoring				
Designation: cracks in the roof				
Probable causes		Yes	No	
	Span increase			
	Stress state variation			
	Vibrations caused by underground mining			
	Others			
Probable consequences (potential risk)		High	Medium	Low
	New fractures			
	Cracks opening increase			
	Rock fall			
	Structural instability			
	Others, ruptures			
Monitoring		No risk	Medium risk	High risk
	Geotechnical analysis of fractures			
	Fractures characteristics			
	Displacements			
	State of strain			
	Others			
Potential risk classification		No risk	Medium risk	High risk
	Urgent actuation			
	Importance for the structural stability			
	Affected production			

Decision Support System is based on a geotechnical characterisation given by the sub modulus named potential risk classification. This sub modulus is built with field and monitoring information that is correlated with mining potential risk, methods of diagnosis and repair. These different information's types have to be related between each other, in an objective way, through matrix correlation.

The potential risk classification is measured in terms of timing actuation divided in three states of alert (none, medium or high risk), for structure stability, production affected and commercial aspects (Table 1).

Following the example described, the IMIS system presents several solutions depending on the potential risk classification. Assuming for structural stability a medium risk, meaning no immediate urgent actuation, the system may suggest some actions to prevent rock fall, like: rock bolting, metallic mesh, shotcrete, etc. If, for example, the convergence velocity is above security levels putting the structure stability in high risk, the system suggests the closure of the mining works and underground access until an expert decision is taken. These two simple examples show that IMIS system has to consider a great number of variables with different weights depending on a specific situation.

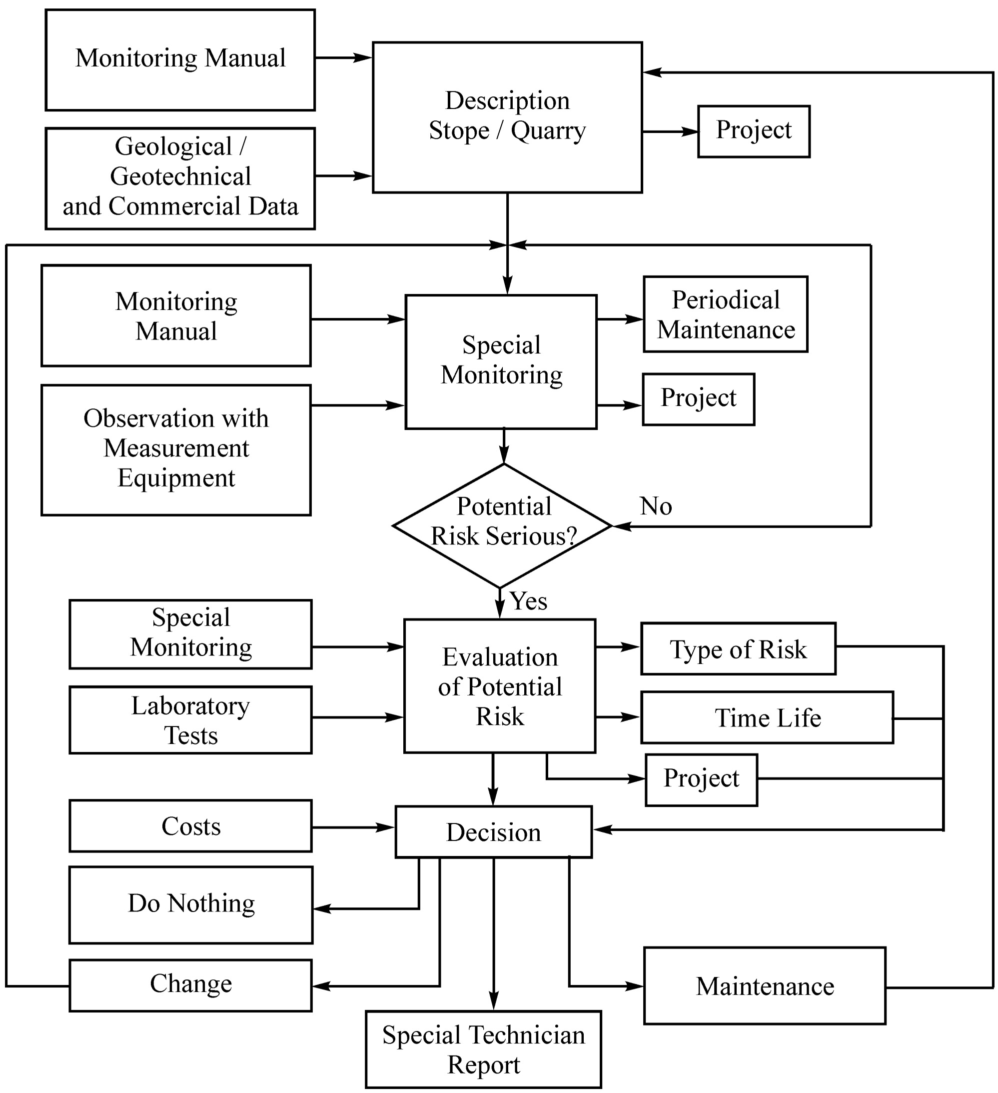

Fig. 1. Example of monitoring procedures in a decision support system

In Fig. 1 it is shown, in a very simple way, how the database, monitoring system and the decision support system are related. The success of this integrated system depends on the way the information of commercial data is determined in real time while excavations are being executed.

CASE STUDY FOR A MARBLE UNDERGROUND EXPLOITATION AT PARDAIS, PORTUGAL

In the case study is presented one methodology that aims to help Portuguese marble industry when applying underground methods in their exploitations. The procedures described were applied to an exploitation localised in the well known triangle (Estremoz, Borba, Vila Viçosa) localised in Alentejo, SE Portugal. The quarry described is designated by Pardais. From all the mining methods alternatives that could be applied to this marble underground exploitation, it was chosen the room and pillar method, where the condition is to abandon these pillars at the end of life of the underground exploitation. The correct pillar dimensioning has to guarantee stability of underground excavations and at the same time minimise marble loss.

Investment for the project under study considers existing structures for the operation at the mining site, and need to add some support infrastructures and equipment related to the new situation of underground exploitation. Table 2 cites the actual exploitation data for Pardais.

Some infrastructures and equipment will of course be shared by both types of exploitation, because of their direct relation. A portion will also be reserved for landscape recuperation.

For the preliminary economical evaluation it was assumed that the company is already extracting marble from quarry mine with 42 meters deep, and this is where underground works will start. It is also assumed that the company owns the land to be exploited as well as some of the support equipment for quarrying that will be used also for underground exploitation, so these investment costs (equipment, land, development operations) were not considered in this new project investment. For calculation purposes, a hypothetical volume reserve of 100000 m^3 was considered.

For the case under study, probing campaigns were made at the target area, allowing geological and geomorphology characterisation (identification of density and natural direction of faults of the rock mass) as well as the zoning of the quality of the marble which could be extracted.

The study of the geotechnical nature of the area was critical, since only the full knowledge of the geomechanical characteristics of the rock mass and rock to be exploited allows the prediction of safety behaviour, and thus, to adopt the adequate quarrying method [2, 3].

If the chosen underground method is room and pillar, with a nominal dimension of pillars in square sections of 6×6m, and stopes with 6 meters wide and maximum pillar height of 14.5 m, subdivided in three levels, the first with 4.5 meters and the remaining two with 5 meters high each.

Using the Theory of Tributary Area for room and pillar dimensioning gives the possibility of analyse the variation of extraction rate, safety factor with pillar width, for a given pillar deep location. With this tool engineers may choose the best combination between safety and extraction rate. Table 3 shows the results of the application of this theory for a marble pillar located at 42 m deep in Pardais quarry.

To support the decision making criterion, pre economical-feasibility analysis were made for three cases as described in Table 3, using safety factors 4, 6 and 8 and for each case, recovery rate was varied (parameter which depends of the ornamental and commercial value of extracted marble blocks) and, for each extraction value a different sales price for the ornamental rock was considered. Thus, groups of results were obtained which allow verifying sensitiveness of economical indicators such as internal rate of return, payback period, and net present value with sales prices, yearly extracted volumes and recovery rate for each of the proposed cases.

TABLE 2. Actual Data from Pardais Exploitation

Field Form — underground marble quarry	
Location (*xyz*): Pardais / Stope D257 — 2nd level	3. Commercial data
Team: A	Matrix color: white
Date: 11.06.2002	Vein color: grey
1. Characterization	Vein density: low
Geotechnical	Block dimension: 15.5 m^3
A. Difference of level is 257 m	Marble commercial designation: Branco de Pardais
Depth 115 m	4. Observations
B. Geology	RMR (rock mass rating): 81, very good quality
Lithology: white marble with grey veins	5. Photos
Weathering conditions: mediumнее	
Water drainage: none	
C. Geomorphology	
Faults: none	
Discontinuities: 70°E, 90° (sp = 0.6 m); N-S,45 (sp = 1.3 m); N15°W, 90° (sp = 1.3 m)	
Other discontinuities: veins, etc.	
D. Geomechanical	
Rock mass	
In situ stress is 2.9 MPa Strength, MPa: Uniaxial compressive strength: 68 Tensile: 6.5 Deformability: 65 MPa Cohesion: 8 MPa Friction: 48° 2. Geometrical data A. Surface — slope angle — height B. Underground structures, roof/floor Span of slopes: 6 m Roof height: 42 m Pillars Section dimension: 6×6 m Height: 14.5 m Slenderness: 2.42	

TABLE 3. Fundamental Geometric Parameters Used

Case	Safety factor	Pillar, m×m	Stope, m		Level height, m	
			width	height	first	Second and third
1	4	4×4	8	10.5	4.5	6
2	6	5×5	7	12.5	4.5	4
3	8	6×6	6	14.5	4.5	5

After selecting the mining method and setting the dimension of exploitation area, it was possible to start selection of proper equipment for the tasks and processes to execute. Equipment and its use annual, labour efficiency and support infrastructures for production give the data to set production capacity. At last, the process used and the mining sequence established set the main lines of economic feasibility of the project for this study, in which all values are considered at constant prices.

Operation costs were divided in fixed and variable costs and operation costs were calculated based on volume of mined rock, and thus costs are independent from mining extraction rate.

According to development staging, underground exploitation is divided between 3 levels with exploitable reserves. Production was defined in line with work chronogram and predefined production volume units which have the duration of 2 months work, with corresponding production varying between 243 m^3 and 519 m^3 per month).

Second and third level will be exploited alternately until year 10, when the team from the first floor moves to the third floor and from this time on both levels will be exploited simultaneous. This is why production reaches its higher value in the two last years, presented in Table 4.

In order to establish different scenarios for economical analyses, a group of four possible cases was studied. Due to high structural and geological heterogeneities, leading to a very difficulty identification of location of marble with good quality, there are great quantities of exploited marble that are sent to waste deposits. It is very important to define different values of recovery rates, 60 %, 50 %, 40 % and 30 %, named optimist, even, conservative and pessimistic, as indicated in Table 4, where is also included yearly commercial production sales in m^3.

For the cases presented were estimated cash flows, using the most probable unit prices of marble exploited underground. In this quarry it is possible to obtain three types of marble, each one with different price values, depending on block dimension. Therefore it was established a medium price for each type of marble. In this case study and based on geological survey campaigns, is expected to exploit three block types: first, second and third category, depending on its aesthetic and blocometry characteristics. So was defined a medium price value for each variety, being 505, 450 and 395 euros/m^3.

For the situations considered, optimistic, even, conservative and pessimistic, and by hypothesis, every block that is exploited is actually sold, can be obtained the results of yearly sales revenues, like those represented in Table 5 for sales price of 450 euros/m^3.

Due to the determination of probable investments amounts, production costs and volumes to exploit, as well as the expected revenues for the commercial quantities pre-defined, cash flows are calculated. The decision criteria adopted to evaluate the attractiveness of this investment, based on the constant prices cash flow are payback period (PB) witch represents the numbers of years the investment is fully recovered (Table 6).

TABLE 4. Exploitation Scenarios with Variable Return Rates and Related Volumes Sold per Year (m^3)

Scenarios	Optimistic	Even	Conservative	Pessimistic
Recovery rate*	60	50	40	30
1, 2 years	1458	1215	972	729
From 2 to 10 years	4572	3810	3048	2286
11, 12 years	6222	5185	4148	3111

*Hereinafter, relative recovery rate (percentage of the maximum possible rate)

TABLE 5. Yearly Sales Volumes with Average Price of 450 euros/m^3

Scenario	Optimistic	Even	Conservative	Pessimistic
Recovery rate, %	60	50	40	30
1, 2 years	656 110	546 750	437 400	328 050
From 2 to 10 years	205 6050	1 713 375	1 370 700	1 028 025
11, 12 years	2 799 900	2 333 250	1 866 600	1 399 950

Observing Tables 5 and 6, and taking as example the case scenario of recovery rate of 50% and average price of 450 euros/m^3, obtains a payback period of 5 years. The value of the net present value (NPV) for the case scenario of recovery rate of 50 % and average price of 450 euros/m^3 and an interest rate of 10% was 8,750.000 euros.

The internal rate of return (IRR) varies between a minimum of 10% for an optimist and 49% for a pessimistic scenario, Table 7, using an average price of 450 euros/m^3.

Results show that Internal Rate of Return (IRR) increased exponentially due to sales price increase and also due to production increase, in all cases (Table 3).

Case 1 is the most pessimistic, Case 3 is the most attractive, and Case 2 is in an intermediate position, leading to the conclusion that room height increase represents economic advantages, through operational cost reduction by m^3 extracted.

If safety factor is changed for Case 1, results are that, for a similar room dimensions width and height, safety factor increases (corresponding to a decrease of proportion of extraction in situ) is economically penalising.

Results also show that changing yearly volume production for the same sales price or for the same proportion of extraction, IRR increases. Therefore, there is a huge dependence on the volumes sold to market.

Figures 2 and 3 show a fixed IRR value, which is hypothetically assumed as 17.5 % , the value used by the company as the lower limit to decision making, sales price variation with recovery rate for the cases under study. After this, economically feasible zones are those standing above the line, and economically non-feasible those standing below the lines corresponding to the proposed cases. Case 1 corresponds to the most pessimistic scenario while Case 3 is the most optimistic. Safety factor variations shows that this geotechnical parameter significantly influences project feasibility, simulations for Case 1 in Fig. 3.

For this simulations, it is of the outmost importance to remember that this a study about pre-feasibility with an accuracy of 10 to 30 % of cost estimation [4, 5], where, for example: for recoveries rates (regarding ornamental value) lower or equal to 20 %, projects would only be feasible if sales prices would be higher than 500 euros per cubic meter and for recoveries rates of 70 %, project becomes feasible if sales prices stand below 150 euros per cubic meter.

TABLE 6. Payback Period with Average Price of 450 euros/m^3

Scenario	Optimistic	Even	Conservative	Pessimistic
Recovery rate, %	60	50	40	30
Payback period, years	4	5	6	10

TABLE 7. Internal Return Rate for Average Price of 450 euros/m^3

Scenario	Optimistic	Even	Conservative	Pessimistic
Recovery rate, %	60	50	40	30
Internal return rate (IRR), %	49	38	25	10

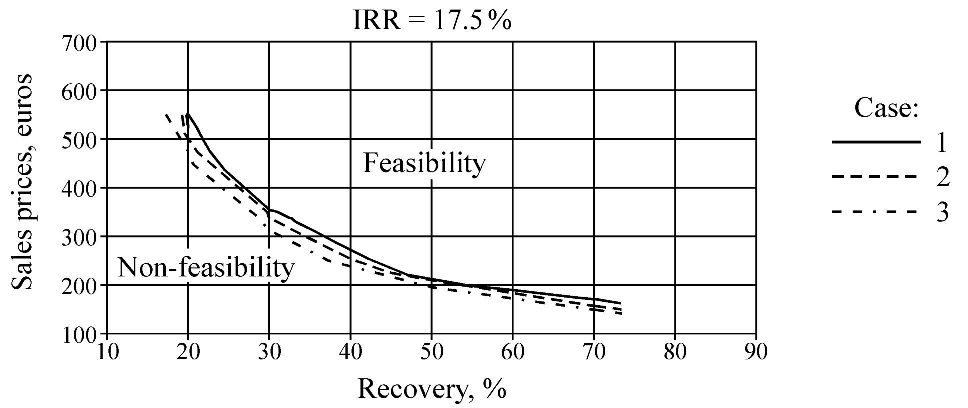

Fig. 2. Sales prices versus recovery rate for the cases considered

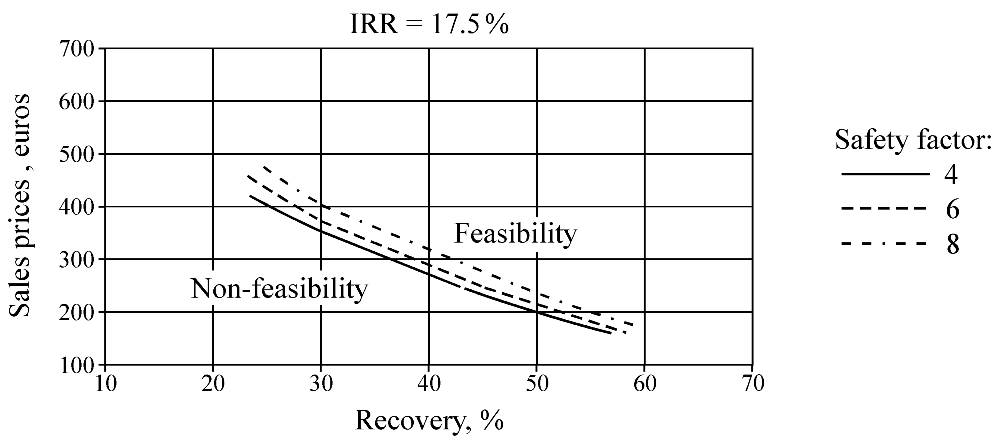

Fig. 3. Sales prices and recovery variation for Case 1 depending on safety factor

CONCLUSION

It was pointed out that even if all actions are well performed and programmed, it is not easy to maintain a correct level of cost, revenues and recovery, when the product has so many characteristics that changes its values in such small mining areas.

But, even when dealing with natural inhomogeneous materials it's absolutely necessary to use a rational management programming. The information can only be used if properly updated, that's why the establishment of these procedures are so important for mining activities.

So, it would be extremely important for this localised marble extraction industry to implement management procedures in order to get support for a more automatic, controlled and accurate planning for future underground marble quarrying, in Estremoz /Borba/Vila Viçosa region.

All the economic indicators are dependent of the volume exploited, the quality of the marble, exploitation costs, recovery rate and sales price.

The parameters that restrains underground exploitation of marble and its economic feasibility, as demonstrated in this study are: quantity and quality of marble exploited; its geotechnical characteristics, both strength and deformability properties that conditioned the stability of underground openings; geometry dimensions of room and pillars; support systems required; extraction methods and systems used; environmental impacts and mitigation; human and materials resources needed for the project; safety, hygiene and health.

The interaction of all these factors, production, geotechnical and ornamental (aesthetic) define the optimal economic conditions of this project. Due to the great sensitivity of economic indicators with the these factors, the study, here presented proves the importance of the correct evaluation of geotechnical properties to establish economic feasibility of this type of investment, that shows to be very promising for the future exploitation of marble in the area of Pardais, Portugal.

REFERENCES

1. M. M. Costa e Silva and P. Falcão Neves, "Management procedures for an underground excavation of marble," *ISRM International Symposium on Rock Mechanics for Mountains Regions*, EUROCK 02, SPG (2002).
2. *Manual de Rocas Ornamentales*, ITGE, Madrid, (1998).
3. Projecto de execução de uma exploração subterrânea de mármores em Pardais, Vila Viçosa, IGM (2000).
4. L. J. Krajewski and L. P. Ritzman, *Operations Management*, Addison-Wesley Publishing Company (1993).
5. L. Cabral, *Economia Industrial*, McGraw Hill de Portugal, Lisboa (1994).