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Methodology for the optimization of mining process in quarries: application for Thung Khuoc marble quarry (Vietnam) and dionyssomarble quarry (Greek)

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ABSTRACT

The mechanical properties of rock mass are dependent on the presence of the discontinuities network. Discontinuities of the nature rock mass play decisive role on the design process and efficiency of dimension stone quarries. A methodology has been developed in this paper to optimize the layout of mining process based on the orientation of the measured fracture sets existed in rock mass. For the development of an integrated computer-aided design and planning methodology for characterization of the dimension of quarries, a decision support system has developed based on a numerical modelling and mine planning software. This paper could help to recover the most stone blocks with the sizes and shape adapted to the market demands for marble quarries.

1. Introduction

Structural geologists commonly measure and analyze orientation of discontinuities in rock mass. These measurements are necessary for analyzing the stability of excavation. The orientation of a discontinuity can be described by the dip angle and dip direction (Priest, 1993). The orientation of a discontinuity set and there are generally influences the stability of the slope or the benches. The combination of discontinuities determine the shape of individual blocks in the rock mass (Nguyen et al., 2014). The properties of discontinuities caused an effect to the stability of rock mass include orientation, persistence, roughness and infilling (Hoek and Bray, 2004).

The stability of the benches depends strongly on the structure of the rock mass. Safety factors are therefore a necessary measure in order to identify the state of stability that is directly related to collapse of the bench which could threaten live of worker.

In dimension stone quarry exploitations such as the quarry, the stability of the slopes can be considered from the aspect of slope cut or from the aspect of a bench or from gallery width. The research we introduce is the result of analyzing data and simulating in the fracture rock environment, which is applied to a mining condition of the dimensional stone quarries. We have used advanced tools for analyzing the data

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of joints and simulating the joint sets. Modelling program RESOBLOK was firstly written by LAEGO and INERIS, basing on the theory of (Heliot, 1988) (Laego-École des Mines de Nancy-INERIS, 2008); (M. Bennani and T. Korini, 2000) and (Merrien-Soukatchoff et al., 2012) which is used to simulate cracking rock mass and the PSMY/Staf module in Mathematica (Verdel, 1999) or Dips (Rockscience Inc, 2003) analyses the data of joint set, applying to this model, (Nguyen et al., 2014) and his research group. The results of numerical models have been used to optimize some of the technical parameters for dimensional stone extraction and ensuring stable bench in the mining operation.

2. Methodological

2.1. Design and planning methodology for dimension quarry

Methodological approach was pursued, developed and used the following set and sequence of components for modelling of the rock structure mass and discontinuity such as interactive geological data base with Mathematica and Dips; visualization tool and interface expert with Mathematica, RESOBLOK (and LMGC90/

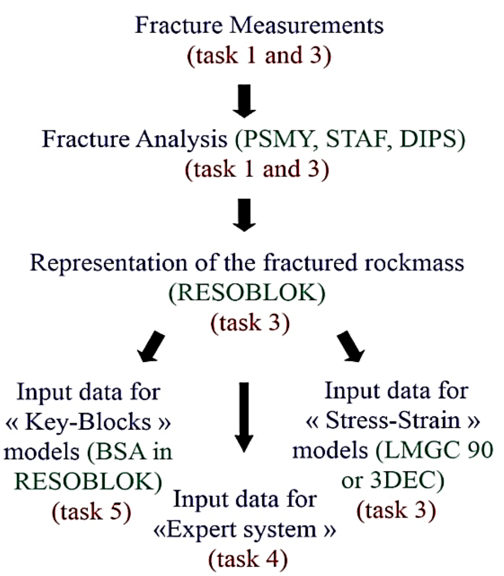

Figure1. Methodological organization for modelling of the rock mass and discontinuity (Thoraval, 2005; Nguyen, 2016; Nguyen et al., 2016): PSMY, STAF and DIPS are the module to analyses the data of joint set; RESOBLOK, BSA in RESOBLOK, LMGC90 and 3DEC are used to simulate cracking rock mass.

3DEC) (see Figure 1). For the design and planning methodology of dimension stone quarry, 7 following tasks need to be performed:

Task 1: Site selection, the main objective is to identify the most suitable work sites and experimental layouts considering the geologic conditions, the quarrying method and the rock mechanics condition relating to problems.

Task 2: Excavation of the experimental site and installation of the instrumentation system. During the progress of the exploitation, all the necessary instrumentation will be installed for the collection of the data required for the computer models in the excavation of experimental quarries.

Task 3: Geomechanical data collection; development of the appropriate 3D rock block models and of the respective geomechanical numerical models.

- The geomechanical and geostructural rock mass characterisation which will provide the input parameters for the computer simulations.

- To obtain a possible data base of rock blocks and rock mass geomechanical for numerical models.

Task 4: Development and use decision support techniques for predicting cost and quality effective quarry layouts. It infers the optimal quarry layout for optimum recovery of saleable blocks, reduced exploitation costs, and optimal rock utilisation from the block modelling.

Task 5: Numerical analyses of database of options (number of discontinuities and sets of fracture obtained) to predict optimum area openings. This predicts optimum site with respect to pillar size, roof span, and reinforcement system for each of the underground exploitations under investigation.

- To determine average block size and shape for each of the quarries.

- Correlation between benches orientations in the fracture network and the recovery and stability of blocks.

The Task 6 and 7 are designed and planned methodology of dimension stone quarry such as:

Task 6: Field investigation of the exploited block size, quality and value. This collects data for the verification of the predictions of the numerical models and of the decision support system for optimum design of the underground openings.

Verification of the rock block models is analysed, and then numerical modelling predictions is obtained, finally it was decision support techniques.

Task 7: Design and planning methodology for dimension stone quarry exploitations. The presentation of the developed and applied techniques in the form of a safety, cost, and quality oriented design and planning methodology for dimension stone quarries exploitations.

2.2. Analysis of fracture measurements

Fracture measurements had been realised in 2 real sites (Thung Khuoc, Vietnam and Dionyssomarble, Greek). The measurements have been done using the scanline method. An analysis has been realised from those measurements with DIPS and PSMY method in order to determine the main sets of orientation and to fit the fracture parameters to statistical laws.

The fractures measurements carried out by the operators have been analysed using PSMY method (Nguyen et al. 2014). This data base (orientation, spacing of fractures) was permitted to determine which statistical laws was used to adjust the various fracture sets. The results of this analysis were compared with those established previously from the fracture measurements conducted at large scale in each quarry.

2.3. Realisation of fracture network simulations

The majority of the measured fractures were introduced in the model using the deterministic generator of RESOBLOK. Other fractures were introduced using the statistical generator (the fractures were simulated using the laws established previously) into the zones where no measurement was carried out. As for the other sites, two successive phases are conducted to build the RESOBLOK model:

- The fracture that have been measured and input to the RESOBLOK;
- Then, inside the zones in which the direct observation is not possible (or where no measurements have been done), different sets of discontinuities have been generated using the statistical laws determined previously (PSMY or Staf). The two kinds of RESOBLOK fracture generator have been used;
- The first one doesn't consider the real fracture extension. Some hierarchic rules have been introduced to make the fractures stop on other fractures (this rule have been defined in order to optimise the representation of fracture network that the first generator can give);
- The second one takes into account the fracture extension assuming that the extension of the fracture in equal to the trace length that has been measured on the wall.

2.4. Minimum block size

According to the technical aspect, block size depends mainly on the parameters of mining system, breakability, transport and processing in the mine. The minimum size (V_{min}≥0.4) of each recoverable block is taken to follow the size of dimensional stone on the market and current technologies. The blocks which have the size V_{min} ≥ 0.4 m^3 usually contain more faults, cracks which requires further processing to complete products from raw dimensional stone. Blocks with the size V_{min}≥ 1m^3 will research to recover.

2.5. Mining optimization to recover maximum blocks

Exploiting dimensional stones were based on the technological phases of cutting blocks from fracture rock environment. The mining system of horizontal layers, vertical layers, and direct transport on the bench and selective blocks are mined to follow the minimum block size V_{min}.

2.6. Mining optimization with stabilizing pit slope

Beside mining optimization to recover maximum blocks, it is possible to determine some technical parameters, the risky problem is caused by bench and pit slope failure in mining operation, which play an important role in the mining effect for a long time. In this study, we choose an assessment method based on limit equilibrium theory to analyze stability slope of quarry. These stiff blocks are analyzed on the basis of stability algorithm including the vector method proposed by Warburton (1981) and Mohr - Coulomb criterion with safety factor FS=1, both of which is set up in RESOBLOK. Totally, there are 10-50 random repeat rounds which have been examined and used to check the stability of all the block on the bench surface.

The distribution of raw block shapes recovered and depends on the fracture of rock mass, mining direction and movement of current benches compared with the direction of the main sets (its mean main family of fracture). Improving a mining effect means to increase the recovery rate and decrease the risk of unsafe problems. Optimizing the recovery rate of dimensional stones being available on the market are a target function of the technical parameters: angle between mining direction and joint set, bench height, dip angle of the current bench.

3. Applications for studies

3.1. Thung Khuoc marble quarry

3.1.1. Analysis of fracture measurements

In this research, the Thung Khuoc quarry, Nghean province, Vietnam was exploited the stone which follows the standard of normal construction materials. The marble stone is able to be used for making various tiles. The dimensional stone products chosen and applied in the calculation and model of the discontinuous rock environment.

According to the result of the exploration report, the Thung Khuoc quarry has estimated reserves of about 10 046 128 m^3: in which the normal construction material reserve is about 9 593189 m^3, the reserves producing tiles and dimension stones are 452939 m^3. The data of joints in the mine are measured by the stations on the surface (8 stations) and joints in drilling cores (5 drilling holes). 3 sets of joints in the mine are identified in Figure 2 and Table 1.

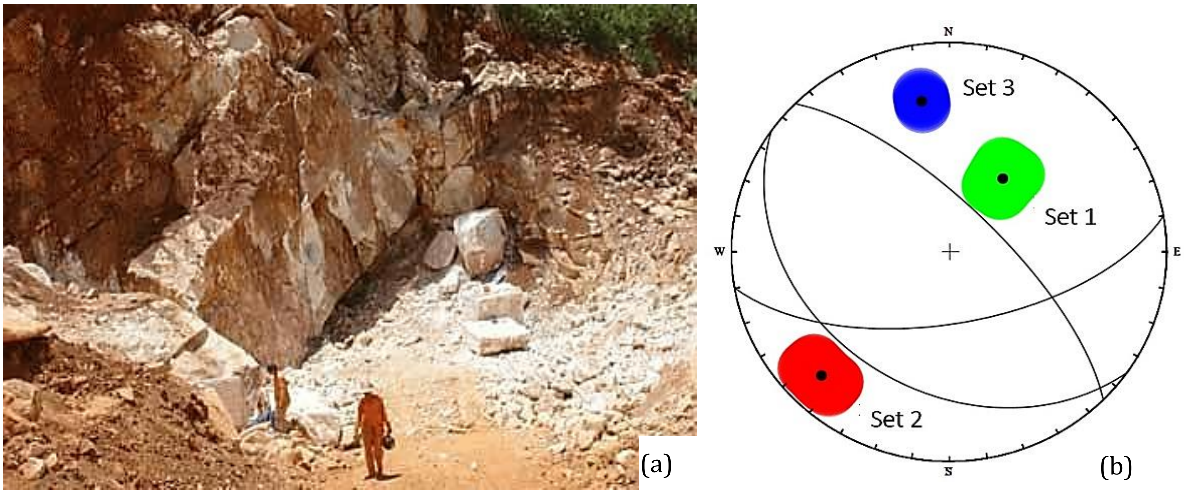

Figure2. Experiment pit M.01 (a) and 3 main joint sets of the Thung Khuoc quarry, (b) Schmidt grid in lower hemisphere.

Table 1. Basic parameters of the key sets in the Thung Khuoc quarry.

Parameters	Sets		
	Set 1	Set 2	Set 3
Dip-direction angle (α_d, degree)	210÷220	40÷50	170
Dip angle (β_d, degree)	30÷40	70÷75	60÷65
Distributing degree of set (K)	220	995	1876
Distance between the sets: uniform (a; b) with a and b are respectively the minimum and maximum values	(0,1;1,25)	(0,1;1,25)	(0,1;1,25)

Table 2. Effect of an average number of blocks in the model of the experiment pit to relationship between the direction of main joint sets and the pit.

The direction of main sets, degree			The direction of the trial mine (degree)	An average number of blocks (blocks)
Set 1	Set 2	Set 3		
210÷220	40÷50	170	35	368
			225	382
			350	404

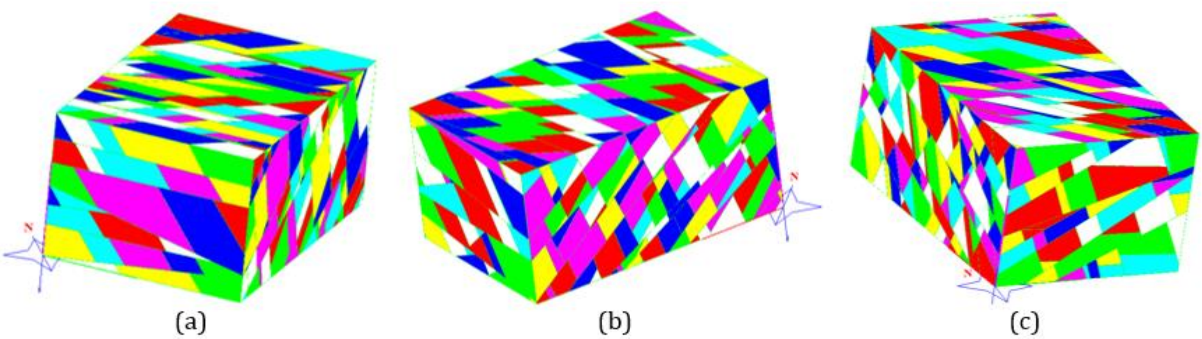

Figure3 Model of fracture rock mass in the experiment pit M.01: direction of the model parallels to set 1(a); set 2 (b); set 3 (c).

3.1.2. Minimum block size

While an average recovery rate of blocks measured with joints on the surface is 20%, in the drill hole is 27.71% and an average rate of joints approached by exploration on the surface and in drill hole is 23.86%.

An experiment pit (M.01) is open with as aim of quantifying the recoverable rate of different size blocks, in fact, taking samples to discover its engineering characteristics. The mine M.01 has 7 m long, 4.8 m wide and 3.5m in average height; its volume is 117.6 m^3.

The result of the pit M.01 has collected 9 blocks with the sizes $V_{min} \geq 0.4$ m^3, all of which have 5.48 m^3 accounting for 4,7% of the volume of the pit.

3.1.3. Establishing of joint sets and mining orientation

By some scenarios of input data and the position of collected joints, we begin simulating the geometric and the mechanical conditions of fracture rock which consists of distinct hard rock by using random statistic algorithms. Joints have not been observed, collected, but they are also to establish the model which comes from the distributing rules of statistics when observing and analyzing a group of the joint data. There are two kinds of the joints used in this condition: infinite-length joints which are affected by the limit of model or other joints in their set; closely polygon-shape joints, strengthening in specific area between the blocks. In addition, the distance between joints in each set is important and to decide block sizes.

Beginning from the exploratory data in the pit M.01 and the initial results on raw stone volume, the pit M.01 was recovered (size, volume and recovery rate) in a typical area of the Thung Khuoc quarry. The model of fracture rock mass in the pit M.01 has been chosen to analyze for optimization purpose of the parameters and the mining direction of the mine such as stabilized bench. The open pit slope ensures mining optimization as well as recovering the maximum size of commercial blocks.

Figure 3 introduces the models of joint sets in RESOBLOK with 3 different mining directions of the trial mine. The results of examinations in each direction considering several various random models are shown in Table 3.

3.1.4. Determination of mining direction

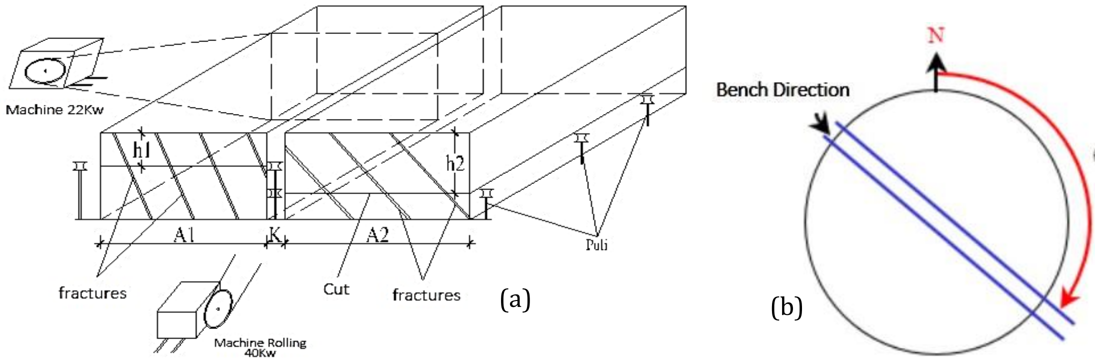

Figure4. Plan of mining technology for dimensional stone by wire saw machine (a) and the moving direction of mining benches (b).

With a main joint set, the angle of mining bench direction is parallel or perpendicular to the main set, which will allow recovering the maximum volume of commercial blocks (V_{min}). Optimization needs to be tackled when more joint sets appears in the discontinuous rock mass, the basic parameters in mining bench direction need to be represented properly in order to be able to optimize in the model.

Figure 4 showing the investigating result of 3 typical mining directions is consequently perpendicular to sets 1, 2 and 3. The results are represented on the distributing histogram with a specific order of blocks being equivalent to model volume (in the left column) and the percentage of the volume of the blocks is equivalent to the mining direction of the experiment pit model (in the right column).

The direction of the mining benches length where blocks mined relates to the first mining bench position of the mine and the direction of the main joint sets. The data distribution in Figure 5 is the distribution of average values collected from a large number of the random statistical model.

- Mining direction of 35^0, the size is with $V_{min} \geq 0.4$ m^3 accounting for 60% and with $V_{min} \geq 1m^3$ accounting for 36%

- Mining direction of 225^0, the size is with $V_{min} \geq 0.4$ m^3 accounting for 60% and with $V_{min} \geq 1m^3$ accounting for 25%

- Mining direction of 350^0, the size is with $V_{min} \geq 0.4$ m^3 accounting for 60% and with $V_{min} \geq 1m^3$ accounting for 28%.

With the result above, the optimum direction involving in the bench direction of 35^0 parallels or is penpercular to primary set direction 1 (set 1), will be able to be recover the most block rate of $V_{min} \geq 1m^3$ accounting for 36%. Difference in the recoverable rate among the blocks with joint measuring methods on the surface (from 18.75% to 21% and an average of 20%), drillcore (from 25% to 28,7% and an average of 21,71%) and mine opening (14.28%) and the numerical model of the discontinuous environment (40%) with a group of the data from the 3 investigating methods on the surface shows that there are, in fact, a lot of invisible cracks which have not discovered when measuring on the surface.

From the results above, the 3rd exploratory methods above are not satisfied with the conditions on the numbers, quality of joint data when analyzing and using them for finding out model results. The joint measuring methods in a straight line on the surface are not ensured real joint data (3 dimension) in the discontinuous environment. The method from exploratory drill has trouble from being certain on the position of steep and very steep joints. In drill hole, specifying the dip-orientated angle of joints has still been a challenging and constraint problem with engineers.

In this condition, the data collected from the trial mine M01 only hold 2% of the mine area (about 33.6 m^2 out of the whole area of 16 thousand m^2 with an altitude of from 100 to 230 m^2). Therefore, updating and complementing the number and the exactness of the data is necessary for some the phrases of the mine to improve the quality and certainty of estimated model.

3.1.5. Mining optimization with stabilizing pit slope

Parameters are first applied to compute for numerical model: the mining bench height H=5m, the mining room's width A = 5m, the mining

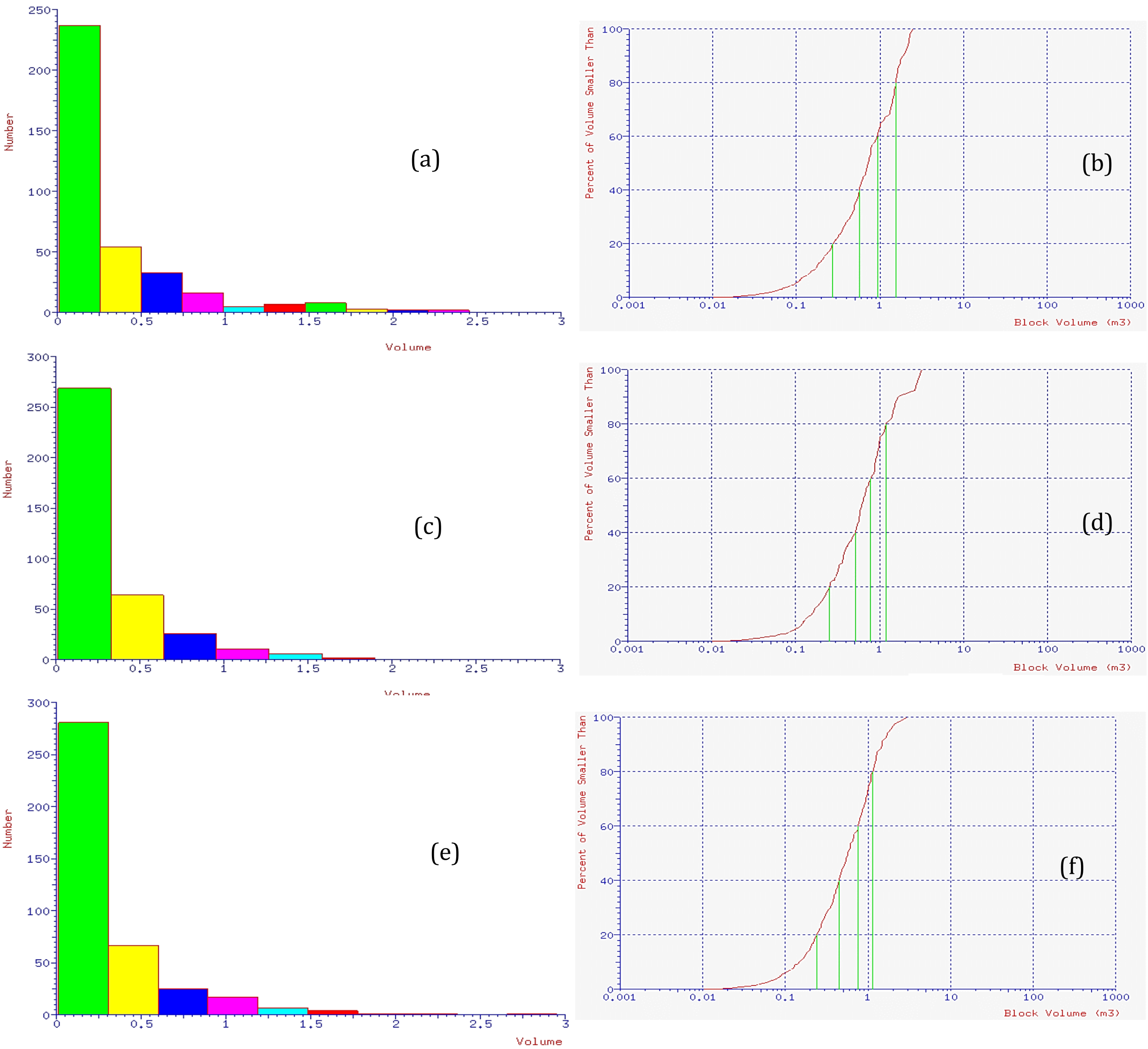

Figure5. Histograms distribute a number of blocks with their volumes in the model (in the left columns) and the percentage of blocks with their volumes (in the right column) which are associated with the direction of the pit: (a, b) 35⁰ direction; 225⁰ direction (c, d) and (e, f) 355⁰ direction.

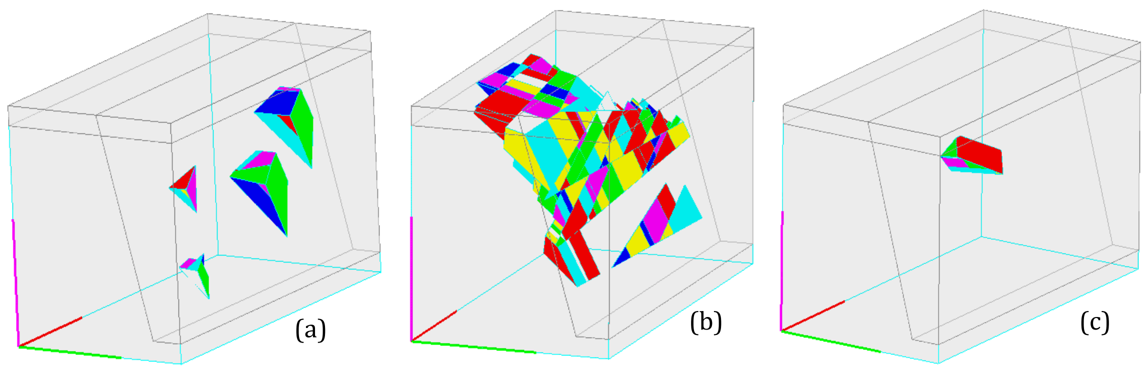

Figure6. Distributing model of unstable blocks on the bench is in a bench direction compared with the North, 35⁰ (a) there are 6 unstable blocks with the volume of 1m³; 225⁰ (b) there are 118 unstable blocks with the volume of 22m³; and 350⁰ (c) there are an unstable block with the volume of 0.52 m³.

room' length L = 10m, where we examine safety condition with the angle of a bench slope α = 75°. The basically mechanical characteristics of rock and joint such as rock density of 2.7 tons/m^3, the joint fiction angle of 30^0, the joint's cohesion of 0, the 3 bench directions (35^0, 225^0 and 350^0) compared with the North are analysed with the stabilities. The result of computing stability on 3 dimension model has the weak structure shown in Figure 5, 6. The analysed results above allow us to select the best mining direction involving recovering and ensuring safe and stability on the bench. When we move the bench with one more mining room, it is possible to see that the volume of unstable blocks in the direction of 350^0 being at right angle to joint set 1 is the least. That means that the developing direction of the mine is safe after that it is in the direction of 35^0. The rest direction of 225^0 has the unsafest risk.

3.1.6. Discussion

Beginning with the ability of the dimensional stone's mining and processing technologies with the minimum block V_{min}, we create an order of developing bench in order to recover the rate having size more than V_{min} accounts for the highest. In this case, the Thung Khuoc quarry in the direction of 35^0 compared with the North develops toward 2 sides, which leads to $V_{min} \geq 0.4$ m^3 accounting for 60% of recovery rate and $V_{min} \geq$ 1m^3 accounting for 36% of recovery rate. Moreover, the developing direction of this bench allows the mine to operate relatively safely with 1m^3 unstable blocks on the 10-length bench.

In the section above, we have already determined the key bench direction of the mine which is perpendicular to the set 1 of 35^0 (set 1) compared with the North. The dip angle of stone layers in set 1 from 30^0 to 40^0. The width and length of mining room are 5m and 10m (some cases depend on particular benches). In some cases of the stable bench, homogeneous rocks are with a dip angle of 90^0. The problem given is to form the target function of specifying reasonable bench height with certainly geological conditions (including dip angle and space between two joints) in order to the most recoverable rate of commercial stones.

3.2. Dionyssomarble experimental site, Greek

In the following, the main activities at the experimental mining site will be demonstrated in the place by the example of Dionyssomarble Co., Greek. The main sets of discontinuity orientation have been determined for each of the 4 pilot sites of the CAD-PUMA project (Thoraval, 2005) from fracture measurements. A fracture spacing law has been evaluated from those measurements. However, because of the actual limitation of the RESOBLOK code, this spacing used in the stochastic simulations, has been finally determined by the in-situ observations (fracture traces on walls and roof of the gallery), Figure 7.

3.2.1. Analysis of fracture measurements

At dionyssomarble experimental site, a continuous monitoring of the dimension, quality,

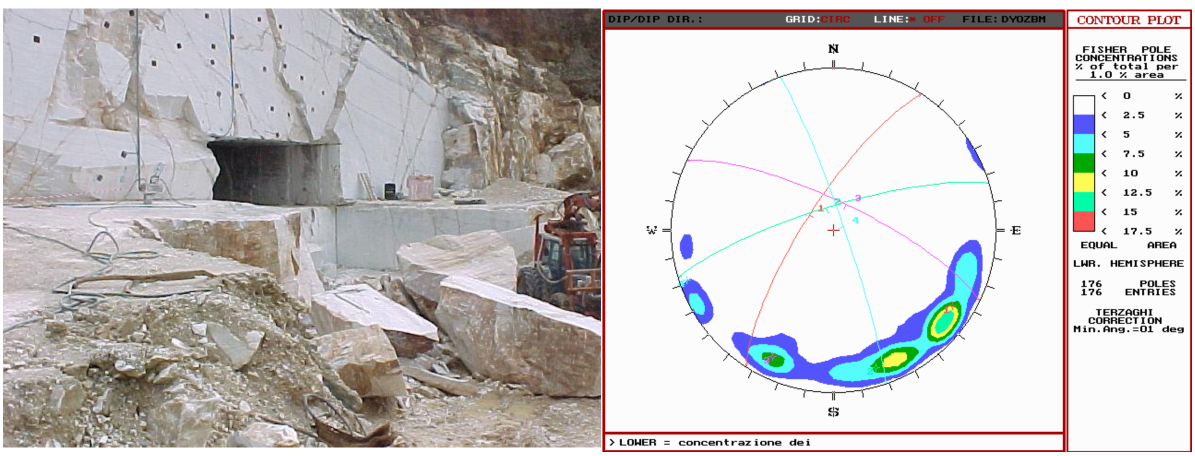

Figure7. Dionyssomarble site B (left) and Representation of the fracture pole concentrations with DIP at Dyonissomarble experimental site (zone B) (right), (Thoraval , 2005).

Table 3. Main sets of orientation at Dyonissomarble experimental site (zone B).

Parameters	Sets			
	Set 1	Set 2	Set 3	Set 4
Dip-direction angle (α_d, degree)	303	339	20	70
Dip angle (β_d, degree)	76	77	78	84
Distributing degree of set (K, no unit)	40	51	29	32

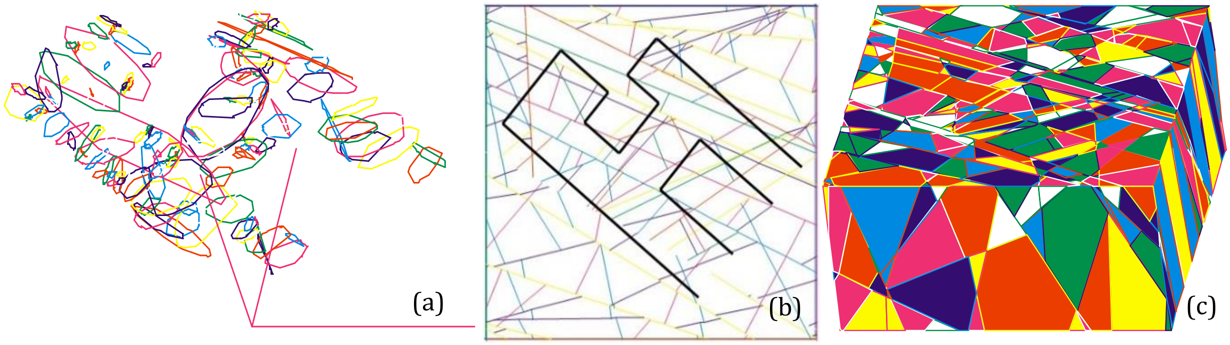

Figure8. Realisation of a deterministic model from the fracture (a), the stochastic model from laws determined previously (b, c) for the Dyonissomarble experimental site (Zone B); Legend: determinist fractures belonging to set 1 (yellow); statistical fractures belonging to set 1 (red); statistical fractures belonging to set 2 (light blue); determinist fractures belonging to set 2 (dark blue); determinist fractures belonging to set 3 (red – they cross all the model); statistical fractures belonging to set 4 (magenta); determinist fractures belonging to set 4 (green).

and quality of blocks quarried in the experimental mines has been carried out as in Table 3. The main objective of the starting phase of the project was the excavation of underground experimental quarries by the three industrial partners. The typical geometry of each site consists of a 9 m wide room around a square pillar having up to 15 m sides. The collected data were then used for the development of the models, which will be used for the simulation of the rock mass fracture net and the rock block database.

3.2.2. Realisation of fracture network simulations

The rock block modelling code (RESOBLOK) was extended to exports data in knowledge-based system format. Blocks can be sorted and analysed according to their size, location, orientation, and continuation (to the depth), Table 4. Rock block data exported to the modelling and mine planning can be analysed with statistical and geostatistical methods. As a result, 3D information about the statistical block distribution can be displayed, giving an idea of the distribution of block sizes in the calculated RESOBLOK model (Figure 8).

3.2.3. Optimisation regarding block recovery

This recovery depends also on the choice of spacing between the cutting plane (1 horizontal & 2 vertical cutting plane). The choice depends on another thing of the possibility to move the block from the quarry to the cutting factory;

To evaluate the block recovery, we will draw a histogram that shows the repartition of the block in 5 classes of volume. The maximum value is in this case 54 m^3; this corresponds to the volume of a cutting block, so 4.5 m (height)* 6 m (width)* 2 m (length in the direction of the gallery axis) when this block is not cut by any fracture.

Table 4. Main sets of orientation at Dyonissomarble experimental site (zone B).

Orientation site	Main set orientation				Actual orientation of gallery	
	F1	F2	F3	F4		
DyoB	110°	250°	212°	160°	306°	36°

The number of blocks in each class is, in fact, an averaging of the result of 10 RESOBLOK simulations. The number of simulations needed comes from verification done for the DyoA site

Table 5. Choice of gallery orientations (angle between the gallery direction and the North).

Orientation site	Main set orientation				Actual orientation of gallery	
	F1	F2	F3	F4		
DyoB	110°	250°	212°	160°	306°	36°

Table 6. Site "DyoB" average number of block.

Orientation	Main set azimut				Actual orientation	
	110°	250°	212°	160°	306°	36°
Average number of blocks in class 5 with a vol. between 43 and 54 m^3; (percentage of the total excavated volume)	9.7 (44%)	9.7 (44%)	11.7 (53%)	11.2 (50%)	7.6 (34%)	11.1 (50%)
Average number of blocks in class 4 or 5 with a vol. between 32 and 54 m^3; (percentage of the total excavated volume)	15.3 (63%)	16.0 (65%)	16.6 (70%)	16.0 (67%)	17.2 (67%)	19.3 (78%)

Table 7. Average total volume of unstable blocks for each gallery orientation (site DyoB).

Orientation	Average volume of unstable blocks (m^3)
110°	826.2
250°	473.7
212°	253.7
160°	168.4
306°	883.7
36°	225.1

(orientation 330°). According to Figure 1, i sis possible to see that when the number of simulation increases, the number of the block in each class of volume seems to become stable. The number of simulation needed to reach the stability is about 20. However, we can see that values are not changing much from the average for 3 simulations to the average for 30 simulations. That why we have considered that 10 simulations are enough to evaluate with a good accuracy the repartition of the block volume. The result can be presented for the site "DyoB" in Table 5 and 6:

- The actual orientation of the gallery (306° and 36°);
- The gallery is oriented parallel to the azimuth of main sets of orientation (set 1: 110°; set 2: 250°; set 3: 212° and set 4: 160°).

The results for the site "DyoB" are presented below in Table 7. The best stability is reached when the gallery orientation is 160° (total volume of unstable blocks = 168.4 m^3). One of the 2 actual orientations of the gallery (36°) gives also good stability result (total volume of unstable blocks = 253.7 m^3). The main unstability is obtained for a gallery orientation of 306° (total volume of unstable blocks = 883.7 m^3) which is the other actual orientations of the gallery.

3.2.5. Evolution of roof block stability with the gallery width

We have study the effect of increasement the gallery width on unstability. This has been done starting from the models use (to study the effect of gallery orientation) considering only one gallery orientation: 36° from the North for DyoB. Three values of gallery width have been considered as 12 m, 18 m and 24 meters. The results are gathered in Table 8. We can see the increasing that depending of the site a linear or a parabolic increasing of the total volume of unstable block with the gallery width.

Table 8. Average total volume of unstable blocks for each quarry extension.

Gallery width	Average volume of unstable blocks (m^3) for DyoB
12 m	225.1
18 m	583.1
24 m	881.1

4. Conclusions

The article shows the discontinuous model of the rock mass in Thung Khuoc dimensional stone quarry, Nghe An, Vietnam and Dionyssomarble experimental site, Greek. From the analysing result of the model, we have chosen the developing direction of mining bench optimizing on the recovery rate and safety in the mining operation. This result allows us to calculate the technical parameters being suitable to pit parameters and gallery width as well as the best direction of the bench. Furthermore, we could choose the best mining methods with the aim of increasing mining effect and output, reducing mining expense and needed investment in mining operation, ensuring safety for dimensional stone quarries. Based on advanced models on the computer, we apply and set up the geometric models of joint sets reliably in the discontinuous environment from the parameters and features of joints. This technology enables predicting the investing expenditure with the most effect and safety in the quarries. Therefore, this could recover the most blocks with the sizes which suit to the market demands.

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