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SOME IMPORTANT FACTS FOR ESTIMATION OF NATURAL STONE DEPOSITS DURING THE EXPLORATION

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During the exploration and determination of natural stone deposits some important criteria should be analyzed. Colour and features of ingredients define decoration criteria. The physical and mechanical properties define technical criteria. Geological criteria should be defined by geological characteristics, especially discontinuities important for determination of exploitation and stone block utilization from rock mass. Discontinuities restrict the dimension (greatness) of the exploited stone blocks. Technological criteria indicate the possibility and quality of cutting, grinding and polishing of natural stone. All the stated criteria influence the economical value of the stone.
The most important step during the exploration is measuring discontinuities present in the body of the natural stone deposit. In the present study a simple mathematical model is applied for the spatial analysis of the discontinuities. The input data are α and β angle (strike and dip of discontinuities). Detailed field exploration, old and new excavation banks and core drilling

are very useful for determination of discontinuity, discontinuity density and discontinuity spatial relations. The results of examination, as well as specific approach in particular deposits, should be utilized for evaluation of natural stone deposits.

Keywords: natural stone, exploration of natural stone, utilization of stone blocks, discontinuity spatial relations

Introduction

Rock mass discontinuity is one of the most basic tectonic fabric characteristics. As a consequence of different stress directions and strains in the rock mass, former tectonic fabric is a subject of change. Fabric consists of different elements which are mutually connected with morphological, spatial, functional and genetic characteristics. Structural elements measured in natural stone deposits can be treated and analyzed as geometry. To improve exploration work it is necessary to carry out preliminary investigation especially measuring data about discontinuities.

The determination of geological capability and capacity of production in dimension stone deposits noted Carvalho et al. (2008). According to authors determination of lithological features, geological structures and fracturing state is very important during the exploration. Dimension stone as a specific non-metallic raw material, regarding deposit conditions, exploitation methods and processing, demands an adequate estimation of dimensioning i.e. optimization of the exploitation in relation to the structural elements. Tomašić (1982, 1994) noted that utilization of stone blocks during the exploitation in dimension or natural stone deposits depends on discontinuity fabric characteristics and used methods of exploitation technology.

Selonen et al. (2000) mentioned the necessity of evaluation of appearance and fracturing of the stone in dimension stone deposits. The importance of estimation amount of marketable dimension stone blocks (MDS) before the extraction from »unit volume« of operation (UVO) in chosen discrete part of dimension stone deposit enables exploitation of separate rectangular and parallelepipedal blocks (Mutlutürk, (2007).

Importance of core drilling during the exploration

Exploration of natural stone deposits is a complex job. Depending on the knowledge scale of certain potential area of natural stone deposit we use simple and cheaper exploration methods. The last and the most expensive exploration method, for determination natural stone deposit characteristics, is diamond core drilling. The results gained by core drilling are extremely important for extrapolation and interpolation of different geological characteristics in deposits. Decoration criteria, intact, quality and quantity of usable stone mass deposit could be determined by core drilling. The results of core drilling are important for drafting geological study of reserves. They also have influence on course of elaboration and dynamics of exploitation from beginning to end when recovery of devastated quarry area should be done. It is important to have drilling equipment which will not cause the stone core to break on pieces if the stone mass shows soundness and intact (Tomašić, et al. 2009). During the core drilling amount of 100 % of stone core must be gained for estimation of utilization, soundness and greatness of stone mass blocks in deposit.

Results

Optimization model of discontinuities spatial relations

In this paper a simple mathematical model for the spatial analysis of the discontinuities in deposit of natural stone is presented. Position of all discontinuities in stone mass can be represented as a plane in Descartes 3D coordinate system. The input data for mathematical model are α and β angles i.e. strike and dip of discontinuity. Mathematical equation in segment form that represents plane (1) defines position of every discontinuity in stone mass.

$$\frac{x}{a_i}+\frac{y}{b_i}+\frac{z}{c_i}=1 \qquad (1)$$

Symbols a_i, b_i and c_i in equation (1) are segments that represent intersections of plane (discontinuity) with axes of coordinate system. Next step in spatial tectonic fabric analysis is calculation of intersection angles ($\varphi_{i,j}$) between i and j discontinuities using equations for two planes (2).

$$\cos j_{i,j}=\frac{A_iA_j+B_iB_j+C_iC_j}{\sqrt{A_i^2+B_i^2+C_i^2}\cdot\sqrt{A_j^2+B_j^2+C_j^2}} \qquad (2)$$

Coefficients of direction of pole to a plane can also be defined (3).

$$A_i=\sin\alpha_i \mathrm{tg}\beta_i;\quad B_i=tg\beta_i cos\alpha_i;\quad C_i=1 \qquad (3)$$

Inserting stated coefficients of direction (3) in equation (2) angle $\varphi_{i,j}$ can be calculated.

According to presented, if n is the number of different discontinuities measured in deposit, then K is number of their intersections (4).

$$K=\frac{n(n-1)}{2} \qquad (4)$$

Angle φ has values between 0° and 90°. Based on experience the criteria of the optimum spatial relation between two discontinuities define favourable position when φ tends to be 0° or φ tends to be 90°. It means that most discontinuities in deposit are mutually parallel or perpendicular. In both cases discontinuity position enables efficient extraction of natural stone blocks.

According to this first criteria of optimum spatial relation between discontinuities is defined when $cos\varphi_{i,j}=1$ or tends to be 1 (where $\varphi_{i,j}$ is angle between two discontinuities) which means that most discontinuities in deposit are mutually parallel or tend to be parallel.

Second criteria of optimum spatial relation between discontinuities is defined when $cos\varphi_{i,j}=0$ or tends to be 0 which means that most discontinuities in deposit are mutually perpendicular or tend to be perpendicular.

A third criterion is that all discontinuities in deposit, regardless parallel or perpendicular, are mutually apart as much as possible. If distance between discontinuities tends to maximum value $l \rightarrow max$ ($l_1, l_2, l_3, l_4, \ldots l_n$, distance between two or more discontinuities) than the utilization and size of stone blocks increase.

Results of spatial analysis could be presented with histogram of frequency distribution or with curves of distribution of angles represented with polynomial regression for certain position in deposit. It is very important to determine number of discontinuity families in deposit.

For more realistic evaluation of optimization spatial relation between discontinuities square parabola was used. Square parabola was gained after normalization of relative frequency with maximum value of $Rf=25$.

On figures below, tree different curves most important for spatial tectonic fabric analysis are indicated. Standard tectonic fabric curve (basic curve) or square parabola, marked with number 1, is the same in both examples (figure 1 and 2). Curve 2 is approximated parabola of second degree and curve 3 consists of data represented with polygon frequency based on equation (2). Represented and tested method enables the optimization of spatial relation between discontinuities in deposit. Graphical display of analyzed curves represented in Figure 1 is based on data measured in quarry Kanfanar from Istria (Croatia). Natural stone Kanfanar or Istrian Yellow is defined as stylolitised oncolitic limestone.

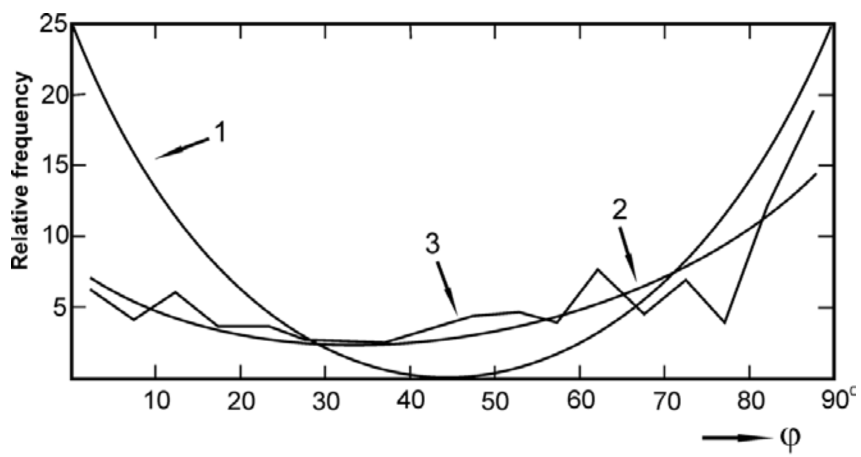

Figure 1: Graphical display of analyzed curves in quarry Kanfanar (Tomašić, 1987).

Graphical display of analyzed curves represented in Figure 2 is based on data measured in quarry Sivec (Republic of Macedonia) where dolomite marble is exploiting.

Both analyzed examples of natural stone deposits displayed in Figures 1 and 2 reveal different degree of favourableness of spatial relation between discontinuities.

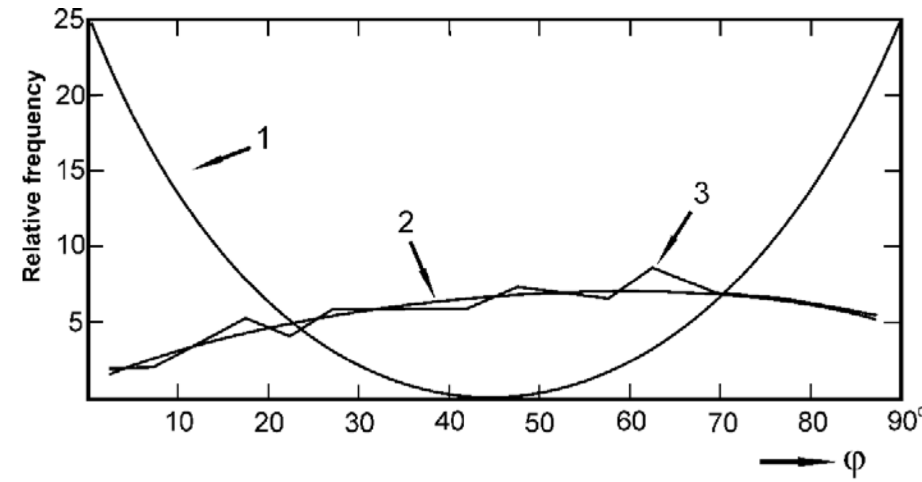

Figure 2: Graphical display of analyzed curves in quarry Sivec (Tomašić, 1987).

Angles of intersections between discontinuities (φ) (figure 1) has maximal values mostly in diagram parts that tends to be 0^o or tends to be 90^o. This example represents favourable spatial relation between discontinuities in natural stone deposit.

Angles of intersections between discontinuities (φ) (figure 2) has maximal values mostly in diagram parts between 50^o and 70^o. This example represents unfavourable spatial relation between discontinuities in natural stone deposit. During exploration in quarry Sivec has been determined that discontinuities are mutually on large distances. According to this the third criteria of optimum spatial relation between discontinuities in represented deposit, when l tends to maximum value, is satisfied. It is the primary reason for exploitation of large commercial stone blocks from deposit.

Exact degree of favourableness of spatial relation between discontinuities can be determined with comparison of curve gained with polynomial regression and with approximated parabola curve or with basic curve.

Relationship between analyzed discontinuities measured in quarries expressed as frequency distribution and standard data expressed as basic curve is important for evaluation of optimization of spatial tectonic fabric relationship in quarry. The main aim of presented analysis is, before exploitation, to determine utilization of stone blocks from rock mass.

Volume utilization of stone blocks

Core drilling is very important during exploration of natural stone deposits. Exploration drilling enables better assessment of stone mass utilization, by means of linear utilization coefficient. Caution should be directed to discontinuities that cuts axis of stone core under angle different then 0^o or 90^o. Detailed exploration of new and old excavation banks and cores from oriented boreholes are very useful for determination of discontinuity, discontinuity density and discontinuity spatial relations. Linear utilization coefficient of rock mass or rock core is calculated using equation (5).

$$K_{uc} = \frac{\Sigma(l_1 + l_2 + l_3 + ...l_n)}{L} \qquad (5)$$

Parameters in equation (5) are:
$l_1, l_2, ...l_n$ – lengths of intact rock core pieces,
L – length of complete rock core,
K_{uc} – linear utilization coefficient of rock core.

These data are measured and calculated analogous toward Rock Quality Designation (RQD) in engineering geology for determination the degree of jointing in borehole cores. Utilization of stone blocks in deposits could be determined with tree exploration boreholes. Linear utilization coefficient of rock core must be determined for each exploration borehole.

Using oriented boreholes that are perpendicular on different discontinuity families enables analyzing intact parts of stone core. According to expected size of stone blocks in deposit different length intervals (*>50, > 100, >150, >200* cm) should be analysed. Next step is determination of linear utilization coefficient of rock core, for every orientation of boreholes, $K_{uc}1$, $K_{uc}2$ *and* $K_{uc}3$. Last step is calculating volume utilization coefficient (K_{vuc}) in deposit by means of equation (6).

$$K_{vuc} = K_{uc}1 \bullet K_{uc}2 \bullet K_{uc}3 \bullet 100\ (\%) \qquad (6)$$

Results gained with represented method are also useful for determination of optimization of orientation of excavation banks in relation to tectonic fabric characteristic (Tomašić, 1989). This is very important during the exploitation and utilization of natural stone blocks from the rock mass in dependence on the tectonic fabric and technology of exploitation (Tomašić, 1994). Determination of stone block utilization must be done very carefully. Distance and intersection angle (φ) between discontinuities can be measured using data from boreholes, outcrops and old excavation banks. According to stated, analysis of optimal spatial relation between discontinuities in deposit can be preformed.

Natural stone Sivac is exploited in quarry Sivac on island Brač in Croatia (figure 3). Sivac is dolomitized limestone. Volume coefficient of utilization of stone blocks is from 25 to 30% and greatest blocks of stone are from 6 to 7m^3. Spatial relation analysis between discontinuities in quarry Sivac from Brač is similar to spatial relation analysis between discontinuities in quarry Sivec (Prilep).

Discusion and conclusion

The presented and elaborated spatial tectonic fabric analysis is based upon a simple mathematical model accommodated for input of geological data, i.e. angles α and β (dip and strike of discontinuity). Favourableness criterion, i.e. optimum of spatial discontinuity relationship, regarding intersections degree (cos φ=0 or tends to be 0, and cos φ=1 or tends to be 1), have been established.

To improve criterion for evaluation of analytical results, a standard or basic tectonic fabric curve was constructed, i.e. square parabola. The analysis point out exceptionally convenient discontinuity relationships in quarry Kanfanar (Croatia) and less convenient in quarry Sivec (Macedonia). In spite of that, a large distance between discontinuities in quarry Sivec enables exploitation of greater commercial stone blocks. According to this the third criteria of optimum spatial relation between discontinuities in quarry Sivec is satisfied because *l* tends to maximum value. Exact degree of favourableness of spatial relation between discontinuities can be determined with comparison of curve gained with polynomial regression and with approximated parabola curve or with basic curve. It was done by means of absolute and squared discrepancies between these curves.

Determination of linear utilization coefficient using oriented boreholes that are perpendicular on different discontinuity families enables better analyzing intact parts of stone core. Three different linear utilization coefficients enable determination of volume utilization coefficient.

Results of core drilling are extremely important for evaluation of natural stone deposits. Better core quality and proper interpretation of core drilling results contribute to elaboration and exploitation of stone deposits. But the results of core drilling need much more time and attention considering that they are one of the most expensive types of exploration method. They enable better evaluation of stone deposits according to decorative, technical and geological criteria. The elements that can determine the intact and utilization of stone blocks from rock mass are especially important. For detail assessment of utilization, it is important detection of any kind of defects that might cause breaking of the core, stone block or slabs during cutting, grinding and polishing, or which might cause it after stone elements and slabs will be inbuilt. Detailed determination of discontinuities, discontinuity density and discontinuity spatial relations is important for evaluation of utilization of stone mass in blocks. According to above stated cost effectiveness and reliance of exploration increase.

Figure 3: Quarry Sivac on island Brač in Croatia (dolomitized limestone).

According to presented facts it is obvious that dimension or natural stone as a specific non-metallic mineral raw material, in regard to deposit conditions, exploitation method and processing demands an adequate estimation of dimensioning i.e. optimization of structural fabric elements, what is achieved in this study.

It is obvious that the utilization of stone blocks in dimension or natural stone quarries depends about discontinuity fabric and technology of exploitation (Tomašić, 1994). It includes implicitly maximal adaptation and concordance between technology methods of exploitation in relation with discontinuity distance, discontinuity orientation and discontinuity intersections presented in this article.

Regarding to stated exploitation of different sizes of stone blocks in the same quarry enables increasing of utilization coefficient.

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NEKI OD NAJVAŽNIJIH KRITERIJA ZA VREDNOVANJE LEŽIŠTA PRIRODNOG KAMENA U TIJEKU ISTRAŽIVANJA

Sažetak

U radu su prikazani kriteriji pogodni za vrednovanje ležišta prirodnog kamena u tijeku istraživanja i eksploatacije. Boja i značajke sastojaka stijene važni su za dekorativni kriterij. Fizičko-mehanička svojstva definiraju tehnički kriterij. Geološki kriterij utvrđuje se na temelju dobrog poznavanja geoloških značajki, posebno na temelju mjerenja i analize diskontinuiteta važnih za eksploataciju i iskoristivost stijenske mase u obliku blokova. Diskontinuiteti svojim položajem i gustoćom ograničavaju veličinu blokova dobivenih eksploatacijom. Tehnološkim kriterijem utvrđuju se mogućnosti obrade prirodnog kamena, tj. rezanje, brušenje i poliranje. Svi utvrđeni i spomenuti kriteriji utječu na materijalnu vrijednost blokova. Jedan od najvažnijih koraka u tijeku istraživanja je mjerenje diskontinuiteta prisutnih u stijenskoj masi nekog ležišta prirodnog kamena.

Posebna pozornost posvećena je bušenju za koje se smatra da je jedan od zadnjih, najvažnijih i najskupljih koraka istraživanja. Istražnim bušenjem se utvrđuju osnovne značajke ležišta te su dobiveni podaci temelj za interpolaciju i ekstrapolaciju raznih atribucija u ležištu.

U radu je prikazan jednostavni matematički model pogodan za prostornu analizu diskontinuiteta. Temeljni ulazni podaci su kutovi α i β (pružanje i nagib diskontinuiteta). Detaljno istraživanje na terenu, na starim i novim frontama otkopavanja te na kamenim jezgrama, vrlo je korisno za utvrđivanje diskontinuiteta, njihove gustoće i njihovog međusobnog prostornog odnosa.

Položaj svakog diskontinuiteta unutar strukturnog sklopa stijenske mase možemo prikazati kao ravninu u Descartesovom pravokutnom koordinatnom sustavu. Pri tome je položaj svake ravnine odnosno diskontinuiteta definiran ulaznim podacima, kutovima α i β (pružanje i nagib), moguće prikazati koristeći jednadžbu ravnine u segmentnom obliku (1). Pritom su a_i, b_i i c_i odsječci koje čini ravnina odnosno diskontinuitet s koordinatnim osima. Daljnjim postupkom, koristeći jednadžbe dviju ravnina, dolazimo do formule za izračunavanje kuta između dviju ravnina u ovom slučaju između diskontinuiteta. Može se odrediti iz izraza (2), gdje je $\varphi_{i,j}$ kut između i-tog i j-tog diskontinuiteta. Prethodnim izračunavanjem, koristeći opći oblik jednadžbe ravnine mogu se izraziti koeficijenti smjera normale na ravninu (3). Njihovim uvrštenjem u jednadžbu (2) dobije se izraz pogodan za izračunavanje kuta između dviju i više ravnina odnosno dva ili više diskontinuiteta.

Pri tome je kut φ kut između *i*-tog i *j*-tog diskontinuiteta. Taj kut iznosi od 0^{o} – 90^{o}. Iskustvo pokazuje da je najpovoljniji prostorni odnos diskontinuiteta u području prema 0^{o} ili prema 90^{o}, što naravno znači da je povoljno odnosno optimalno ako su u ležištu diskontinuiteti međusobno paralelni ili okomiti. Tada će, dakako, formiranje pravilnih blokova biti mnogo lakše i učinkovitije tijekom eksploatacije u ležištu. Prvi kriterij optimalnosti može se izraziti kao $cos\ \varphi_{i,j} = 1$, a to znači da su diskontinuiteti međusobno paralelni odnosno da njihov međusobni presjek teži prema 1. Drugi kriterij optimalnosti može se izraziti kao $cos\ \varphi_{i,j} = 0$, a to znači da su diskontinuiteti međusobno okomiti odnosno da njihov međusobni presjek teži prema 0. Treći optimalni uvjet je da svi diskontinuiteti u ležištu, bez obzira da li su skloni biti međusobno paralelni ili okomiti, budu na što većem razmaku odnosno da $l \rightarrow max$ ($l_1, l_2, l_3, l_4, \ldots l_n$, razmaci između diskontinuiteta teže maksimumu). Ukoliko su razmaci veći, utoliko se iz stijenske mase mogu dobivati veći blokovi.

Rezultati se prikazuju pomoću histograma distribucija frekvencija ili pomoću krivulje distribucije kutova dobivenih polinomnom regresijom za određenu poziciju u ležištu. Potrebno je još utvrditi dominiraju li u ležištu tri ili više sustava diskontinuiteta. Da bi se dobila što realnija ocjena povoljnosti međusobnog položaja diskontinuiteta, upotrijebljena je reperna krivulja (kvadratna parabola) koja je dobivena normalizacijom relativne frekvencije pomoću maksimalne vrijednosti relativne frekvencije Rf =25.

Na sl.1 vidljiva je prepoznatljiva reperna krivulja (1) koja je uvijek ista. Krivulja (2) je aproksimirana parabola drugog stupnja, a krivulju (3) čine podaci prikazani poligonom frekvencije dobiveni temeljem jednadžbe (2). Razrađena i testirana metoda omogućuje optimiranje prostornog odnosa diskontinuiteta. Analiza prikazana na sl. 1 temelji se na podacima izmjerenim u kamenolomu Kanfanar u Istri u kojemu se eksploatira *onkolitni* vapnenac poznat pod komercijalnim nazivom *Kanfanar* ili *Istarski žuti*. Analiza prikazana na sl. 2 temelji se na podacima izmjerenim u kamenolomu Sivec (Makedonija) u kojemu se eksploatira dolomitni mramor komercijalnog naziva *Sivec*.

Stavljanjem u funkcionalnu vezu rezultate dobivene prikazanom analizom s rezultatima utvrđivanja razmaka između diskontinuiteta omogućuje vrednovanje povoljnosti međusobnog položaja diskontinuiteta u strukturnom sklopu stijenske mase. Cilj takvih analiza je unaprijed procijeniti mogućnosti eksploatacije većih ili manjih kamenih blokova prirodnog kamena iz stijenske mase. Ukoliko je moguće, razmaci diskontinuiteta se mogu mjeriti na površini terena, na otkopnim frontama kamenoloma ili na kamenoj jezgri iz bušotina.

U tom je pogledu posebno važno istražno bušenje na jezgru. Istražna bušotina do određene mjere omogućuje procjenu cjelovitosti pomoću linearnog koeficijenta cjelovitosti. Posebnu pozornost potrebno je posvetiti diskontinuitetima koji os jezgre sijeku pod nekim kutom koji je bitno različit od 0^{o} ili 90^{o}. Na radnim (otkopnim) frontama novih i starih radilišta te na orijentiranoj jezgri iz bušotina moguće je dobiti stvarne razmake diskontinuiteta u ležištu. Linearni koeficijent cjelovitosti izračunava se prema formuli (5).

Ovaj se podatak mjeri i izračunava na sličan način onom koji se koristi kod ocjene raspucanosti u inženjerskoj geologiji pod nazivom RQD (Rock quality designation). Monolitnost odnosno kompaktnost stijenske mase u ležištu u prostornom pogledu može se najtočnije odrediti pomoću tri bušotine. Pritom se analiziraju cjeloviti intervali jezgri iz bušotina koje su prethodno orijentirane okomito na pojedine pukotinske sustave u ležištu.

Za svaku se bušotinu posebno određuje koeficijent linearne cjelovitosti. Cjeloviti dijelovi jezgri $l_1, l_2, l_3 \ldots l_n$ analiziraju se posebno za pojedine intervale dužina, npr. *>50, > 100, >150, >200* cm itd., već prema tome kakvi se blokovi očekuju u stijenskoj masi. Nakon toga linearni se koeficijenti $K_{uc}1$, $K_{uc}2$ i $K_{uc}3$ izračunavaju za svaki smjer bušenja posebno, prema već prethodno spomenutim ograničenjima i dobivenim intervalima jezgri. Naposljetku se izračunava stvarna ili volumna iskoristivost stijenske (K_{vuc}) mase u ležištu prema formuli (6).

Rezultati dobiveni prikazanom metodom analize mogu se također korisno upotrijebiti i kod određivanja optimalnog položaja otkopne fronte u odnosu na položaj učestalih diskontinuiteta. Ovo je vrlo važno kod eksploatacije i iskorištenja stijenske mase u obliku blokova u ovisnosti od strukturnog sklopa i tehnologije eksploatacije.

Utvrđivanje cjelovitosti stijenske mase mora se pomno provoditi. Izmjereni razmaci i položaji diskontinuiteta u bušotinama, na površini terena i na otkopnim frontama starih radilišta mogu se analizirati na način da im se odredi optimalnost međusobnog prostornog odnosa mjerenjem i analizom kuta φ između diskontinuiteta te mjerenjem razmaka između njih.

Na sl. 3 prikazan je kamenolom dolomitiziranih vapnenaca na otoku Braču. U kamenolomu se eksploatira varijetet prirodnog kamena *Sivac* uz volumni koeficijent iskoristivosti kamenih blokova od 25 – 30 %. Ponajveći blokovi dosežu veličinu od 6 – 7 m^3. Položaji diskontinuiteta slični su onima u kamenolomu Sivec u Makedoniji gdje se eksploatira varijetet prirodnog kamena *Sivec* (dolomitni mramor).

Prikazan matematički model jednostavan je i pogodan za analizu izmjerenih diskontinuiteta. Rezultati istraživanja i analize diskontinuiteta vrlo su korisni za vrednovanje stijenske mase u ležištima prirodnog kamena i prognoziranje njene iskoristivosti i održive eksploatacije.

Ključne riječi: prirodni kamen, istraživanje prirodnog kamena, iskoristivost stijenske mase, prostorni odnos diskontinuiteta

Napomena:
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