MGPB

The optimization of technological mining parameters in a quarry for dimension stone blocks quality improvement based on photogrammetric techniques of measurement

The Mining-Geology-Petroleum Engineering Bulletin
UDC: 622:35
DOI: 10.17794/rgn.2018.2.8

Original scientific paper

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Abstract
This research focuses on patterns of change in the dimension stone commodity blocks quality production on previously identified and measured geometrical parameters of natural cracks, modelling and planning out the final dimension of stone products and finished products based on the proposed digital photogrammetric techniques. The optimal parameters of surveying are investigated and the influence of surveying distance to length and crack area is estimated. Rational technological parameters of dimension stone blocks production are taken into account.

Keywords
Dimension stone, granite blocks, cracks, mining surveying, image processing, photogrammetry

1. Introduction

The main problem which dimension stone mining enterprises in the Ukraine are facing is an introduction into the production of new technologies, international standardization and certification of dimension stone block production of granite, labradorite, gabbro and other natural stone deposit types. The researchers showed that in addition to qualitative and quantitative losses, there are commercial losses, i.e. stone loss from inaccuracy in commodity block commercial size and volume definition. The reason for such losses is the lack of an accepted standardized way to measure geometric dimensions of commodity blocks and a significant error in measurements by traditional means.

The study of cracks is the basis for quality commodity products control for stone mining enterprises. The study of cracks and dimension stone rock mass blockiness was done in (**Karasev and Bakka, 1997; Kosolapov, 1990; Pershin et al., 2015; Elci et al., 2014**). In articles (**Mosch, 2011; Luodes and Sutinen, 2011; Assali et al., 2014; Kalenchuk et al., 2006; Nguyen, 2011**) the authors used digital images of sites with natural stone array cracks for measurement of the crack parameters of natural separateness. In articles (**Deliormanli et al., 2014; Sonmez et al., 2004; Yavuz et al., 2005; Reid and Harrison, 2000**) the procedure of processing rocky surface digital images for separate crack identification is investigated. Mining operation planning methods on a quarry were investigated on the basis of digital image analysis of ledge surfaces by taking into account given sizes of block output (**Ülker and Turanboy, 2009; Alade et al., 2012; Elci and Turk, 2014; Mutlutürk, 2007**). Development of a high-performance technique of natural crack structure visualization with standard surveying instruments, such as a theodolite and a compass-clinometer was a main research objective (**Turanboy, 2008).** In their research (**Ahmadabadian, 2013; Luhmann et al., 2014; Kemeny, 2006; Lemy and Hadjigeorgiou, 2003; Luodes and Sutinen, 2011**) present the technique of crack surface three-dimensional model creation on the basis of multi-source data.

Reliable information about cracks and deposit blockiness allows for the determination of the coefficient of dimension stone commodity block output, a rational direction of mining operation front movement, to determine the equipment set for the extraction and processing of dimension stone (**Karasev and Bakka, 1997; Caranassios et al., 2000, Sonmez et al., 2004; Yavuz et al., 2005; Caranassios, 2000**). To receive the output data about dimension stone cracks with the purpose of further determination of its blockiness, the photogrammetric method is used.

Despite the fact that theoretical and practical work is conducted in this area, a comprehensive study assessing the quality of raw materials for the production of dimension stone blocks is not performed, which indicates the relevance of research in this area. The study of the problem indicates insufficiency in the scientific-practical bases application of digital photogrammetry methods for the purpose of quality control in dimension stone blocks.

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The solution of this problem requires: study of the accuracy of natural separateness linear dimension measurement by digital methods; development of methods for determining their quantities, crack detection methods (**Levytskyi and Sobolevskyi, 2014**); the subsequent rational technological parameters of mining operations definition with the adjustment of the front work direction development at a particular manufacturing quarry site.

2. Material and methods

A digital non-metric camera Samsung S1050 was calibrated and used to determine optimal photogrammetry surveying parameters. This camera was used to research the commodity blocks surveying the accuracy of Leznikivske, Pokostivske and Bystryivske deposits, and also for the surveying of Natalyivske deposit rock mass.

To determine the subject point coordinates, namely commodity blocks or dimension stone massif, depending on the surveying conditions, 3 stereophotogrammetric surveying cases were considered: normal, uniformly rejected and convergent. The dependence of the accuracy of determining the spatial coordinates m_y converged in case, surveying (x = 7.2 mm, z = 5.3 mm, f = 24 mm, m_p = 0.005 mm) on the convergence angle γ and the basis of surveying B is shown in **Figure 1**.

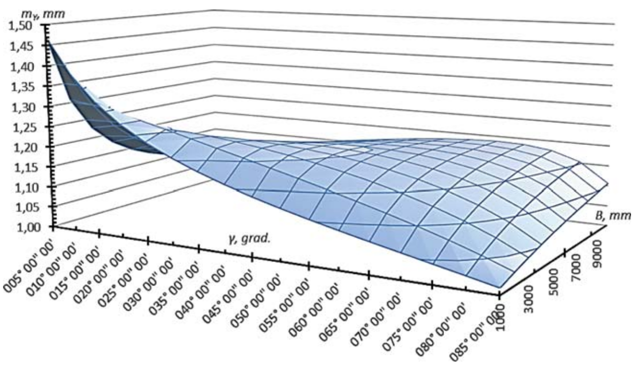

Figure 1: The dependence of the accuracy the spatial coordinates m_Y from convergence angle γ and the basis B in the case of convergent surveying

The results of the coordinates definition accuracy comparison at the normal and convergent surveying cases for the given parameters of the study showed that convergent imagery does not impose restrictions on the conditions of photography and allows to survey in difficult conditions for any dimension stone quarry. To obtain the dimension stone commodity block coordinates, three phototheodolite surveying methods and schemes were used: 1) surveying with four base points around the block and the way straight serifs; 2) surveying with two base points with the visibility of all block faces; and 3) surveying with a basic point and visibility of the two block sides (**Levytskyi, 2012**).

To justify the effectiveness of the above methods and survey research, the calculations were based on the required accuracy. Land digital surveying of a commodity block was performed on Pokostivske, Leznikivske and Bystryivske deposits by a digital camera Samsung S1050 and theodolite 2T30. To connect a digital camera with a theodolite, a removable attachment consisting of a laser tape measure and a cylindrical level was used, which was designed to synchronize movement of the theodolite and camera.

Analysis of the dependence of the maximum distance surveying Y_{max} from the basis B and the required accuracy of point coordinates on the y-axis m_y is shown in **Figure 2**, which leads to the conclusion that to ensure II accuracy category measurement of dimension stone block sizes, the maximum surveying distance should not exceed 7.5 m.

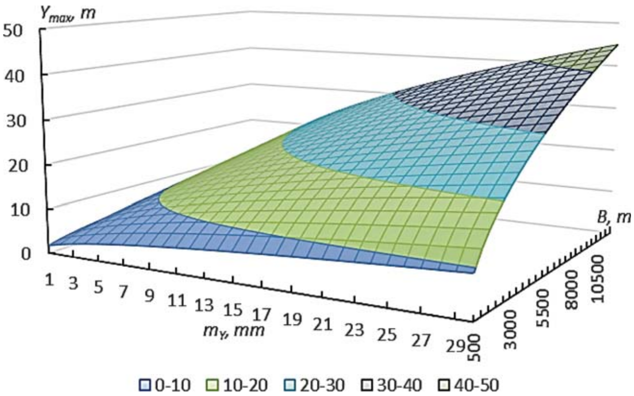

Figure 2: The dependence of the maximum distance surveying Y_{max} from the basis B and the required accuracy determination of points coordinates m_Y on the y-axis

On the basis of 17 images of the object from different angles with an interval of 10°, the dependence of accuracy Δa of the determination commodity block linear dimensions from the surveying angle α is shown in **Figure 3**.

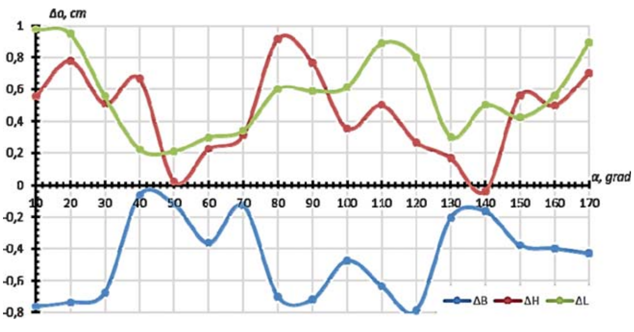

Figure 3: The dependence of accuracy Δa of determination commodity block linear dimensions from the surveying angle α

The analysis of graphic dependences allows for the determination of the optimum angles of photography

40°, 50°, 90°, 130° and 140°. The dependence of the accuracy of determining the width f (ΔB), length f (ΔL) and height f (ΔH) of commercial blocks from a distance convergent photogrammetric survey in the form of a second order polynomials:

$$f(\Delta B) = 0,0012L_a^2 - 0,358L_a + 0,3805;$$
$$f(\Delta L) = -0,0918L_a^2 + 0,743L_a - 0,655; \qquad (1)$$
$$f(\Delta H) = -0,0965L_a^2 + 0,815L_a - 0,611.$$

Further statistical analysis was obtained by remote-sensing measurement of jointing indicators and decorative stone properties, they made it possible to determine the zones with increased fracture, to simulate natural cut individually on commercial blocks, to justify the method of determining the commercial block size, to create the passport of final marketable block products of a quarry and to adjust the optimal direction of work scope development. To create the diagnostics status of an array or other objects of a quarry, there is a need to justify the accuracy of the crack system parameters for identification and measurement.

To analyze the array surface developed, the application "Crack Detector" ("CrackStone v1.0") was used. It allows for the analysis of the qualitative state of a rock mass, which further gives the possibility to predict the output blocks. Tachometry surveying through the use of tachometers Sokkia Set 550RX was applied to the assessment of accuracy of the executed measurements. Mining process supervision and geometrical parameter control of block stones at the Natalyivske granodiorite deposit massif were applied. It was executed by a technique described in (**Levytskyi and Sobolevskyi, 2014**) with the subsequent graphic and analytical analysis in the application "Passport of commodity block" (**Levytskyi, 2012**).

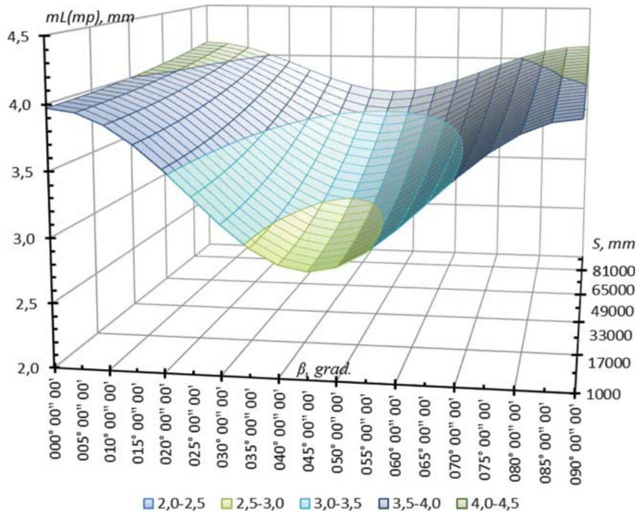

Figure 4: The dependence of the accuracy of determining the crack length $m_{L(mp)}$ from the distance S and surveying horizontal angles β

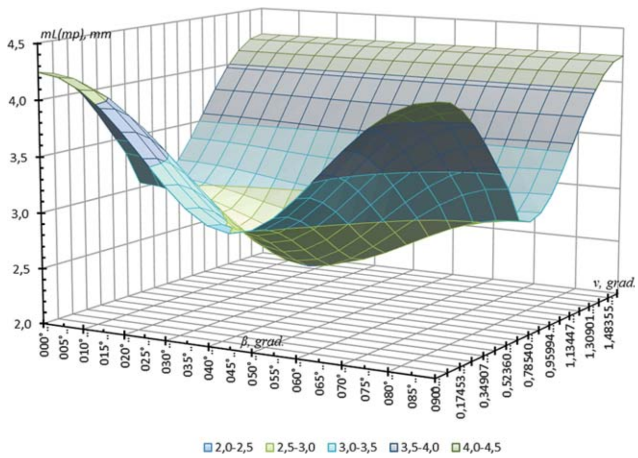

Figure 5: The dependence of the accuracy of determining the cracks length $m_{L(mp)}$ from the vertical and horizontal angles β

3. Results and discussion

The main parameters for the quality of identification of cracks made their length L_{mp} and area S_{mp}. An experimental study to determine the coordinates of the crack points by the method of polar notches was made under the conditions of the Pokostivske granite deposit. The dependence of the accuracy of spatial coordinates of crack points, length and crack area for determined boundary conditions are depicted in **Figure 4** and **Figure 5**.

Analysis of the obtained graphic dependences has allowed to establish that the minimum value of mean square error of the length of the cracks is achieved at horizontal angles in the range of 40^0-50^0, vertical – 30^0-40^0. Therefore, the error of the coordinates, length and area of cracking within the accepted limit values S - [1;100], β,ν - [0;85^0] and the above optimal values of linear and angular parameters tachometric surveying have the following meanings: $m_{L_{mp}}^{\min}$ = 2.45 mm, $m_{L_{mp}}^{\max}$ = 4.21 mm, $m_{S_{mp}}^{\min}$ = 4.66 mm^2, $m_{S_{mp}}^{\max}$ = 29.32 mm^2 corresponding to the II class of accuracy. As a result of studies of the crack identification effectiveness, it was found that the length and crack area deviation from the reference value in the application of complex Niblack-Roberts is respectively 20 % and 24 % (**Levytskyi, 2017**). Complex Niblack-Canny shows a close relationship (deviation 4-6 %) between the reference and calculated values of fracture, therefore this method is chosen as the main algorithm for crack recognition by the author's patented software "Crack Detector".

On the basis of digital camera results which were performed to study the dependence of the accuracy of the length mL_{mp} and square mS_{mp} cracks from the surveying distance. The expected accuracy of determining the length and cracks area to the surveying distance L_{ϕ} can be represented in the analytical dependences form:

$$L_{\phi}(mL_{mp}) = -0,00004mL_{mp}^2 + 0,0006mL_{mp} + 0,0015. \quad (2)$$

$$L_{\phi}(mS_{mp}) = -0,00007mS_{mp}^2 + 0,0016mS_{mp} + 2,1138. \quad (3)$$

To obtain the most reliable information about possible optimal cutting schemes of natural separateness and the maximum commodity block output, it is proposed to take the specific fracture as the main criterion. The result comparison of specific fracture determination and the direct measurements with remote on the Natalyivske granodiorite deposit is shown in **Figure 6**. As shown by statistical processing of measurement results, the error of specific fracture determination is 6 %.

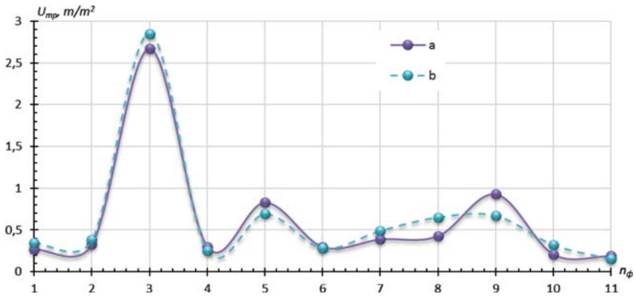

Figure 6: The result comparison of specific fracture determination U_{mp} immediate and remote measurements for the appropriate photos number n_{ϕ} (where *a* – direct measurements, *b* – remote measurements)

A three-dimensional model of dimension stone block creation and determining its volume executed in software «K-Mine» and «PhotoScan Pro» (see **Figure 7**). Digital block surveying was performed according to the above described method. As a result of processing data, block gross volume was defined as 1.78 m³.

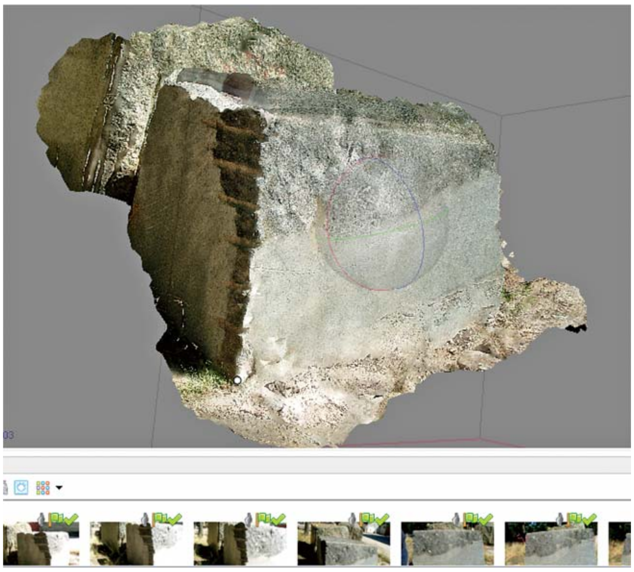

Figure 7: Three-dimensional model of dimension stone block creation by «PhotoScan Pro»

To automate the main block size calculation, in particular commercial unit volume, and connection of all the above sections in a single form-blank was developed by the program «Passport of commodity block» («Block-Stone v1.0») on the basis of Borland and implemented. The program «Passport of commodity block» includes two additional modules «Crack Detector» («CrackStone v1.0») and «Cutting block» («CutStone v1.0»). The module «Cutting block» allows you to select a product, set its size and the thickness of the cutting operations on the cutting block and the treatment of slabs. Input data is the slab dimensions that are automatically calculated by the application with a commercial block size.

One of the main indicators to measure the performance of complex equipment and to prepare units to the recess is the output blocks ratio of k_{bl}, which includes the loss factor of k_m, namely quantitative and qualitative loss of block raw materials, and depends on the technological parameters of the block preparation to the recess.

The technological dependence of the loss coefficient $k_{m.a}$ from the height and length of granite blocks, which are separated by using diamond-rope systems (**Korobiichuk, 2007; Korobiichuk, 2012; Korobiichuk et al., 2016**) once the scheme of extraction, is shown in **Figure 8** and described by the equation:

$$k_{m.a} = \frac{d_{i.a}}{an_1} \oplus \oplus \frac{\pi\begin{bmatrix}(d_{cв}^2 + \sigma_{cm}an_1)^2 an_1 + (d_{cв}^2 + \sigma_{cm}bn_2)^2 bn_2 \oplus \\ \oplus(d_{cв}^2 + \sigma_{cm}hn_3)^2 hn_3\end{bmatrix}}{4d_{cв}^2 abhn_1n_2n_3}, \quad (4)$$

where:

- $d_{i.a}$ – rope outer diameter taking the offset into account (m),
- $d_{cв}$ – diameter wells for packed rope ($d_{cв}$ = 80-110 mm),
- s$_{cm}$ – the rocks strength in compression (kg/cm²).

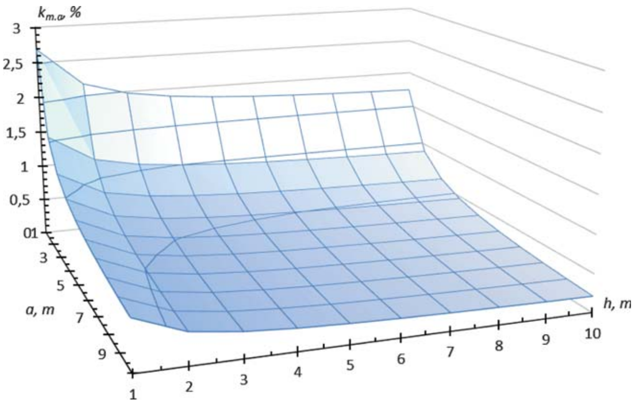

Figure 8: The technological dependence of the loss coefficient $k_{m.a}$ from the height and length of blocks (*b* = 1.5 m) at using diamond-rope systems

Total geological losses are due to non-orthogonally the main cracks systems:

$$
\begin{aligned}
k_г = {} & \frac{l_q^2 n_q ctg\alpha_q \sin^2\gamma_{QL} + 0,5(n_l l_l)^2 \sin 2\alpha_q + 0,5 n_l n_q l_q^2 \sin 2\gamma_{QL}}{0,5\left(n_l l_l\right)^2 \sin 2\alpha_q + n_l l_l n_q l_q \sin\gamma_{QL}} \oplus \\
& \oplus \sin\alpha_q \sin\alpha_s \cdot \frac{\left(l_q^2 n_q ctg\alpha_q \sin^2\gamma_{QS} + 0,5(n_s l_s)^2 \sin 2\alpha_q + 0,5 n_s n_q l_q^2 \sin 2\gamma_{QS}\right)}{\left(n_q l_q \sin\gamma_{QS} + 0,5 n_l l_l \sin 2\alpha_q\right)\cdot\left(n_s l_s \sin\gamma_{QS} + 0,5 n_l l_l \sin 2\alpha_s\right)} \oplus \\
& \oplus \frac{l_q^2 n_q ctg\alpha_q \sin^2\gamma_{QL} + 0,5(n_l l_l)^2 \sin 2\alpha_q + 0,5 n_l n_q l_q^2 \sin 2\gamma_{QL}}{0,5\left(n_l l_l\right)^2 \sin 2\alpha_q + n_l l_l n_q l_q \sin\gamma_{QL}},
\end{aligned}
\qquad (5)
$$

where:

- n_q, n_s, n_l – the number of the separateness between the Q planes respectively transverse, longitudinal L and sloping S crack array within the linear dimensions of the monolith,
- l_q, l_s, l_l – the distance between the planes of the respective systems of cracks (m),
- α_q, α_s, α_l – angles of incidence of the corresponding systems of cracks (grad),
- γ_{QL}, γ_{QS}, γ_{SL} – the angles between the corresponding systems of fractures, which determine as non-orthogonal crack systems between each other (grad).

Therefore, for given fracture parameters using **Equation 5** the geological loss factor k_g can be determined, which for conditions of the Western section of the Natalyivske deposit when $n_q = 3$ and $n_s = 1$, $n_l = 1$, $l_q = 2.5$ m, $l_s = 2.7$, $l_l = 6.0$ m, $\alpha_q = 88^0$, $\alpha_s = 82^0$, $\alpha_l = 5^0$, $\gamma_{QL} = 83^0$, $\gamma_{QS} = 77^0$, $\gamma_{SL} = 65^0$ will amount to 71.5 % (see **Figure 9**).

Geological conditions have no effect on **Equation 5**, which can be used for other dimensions of stone deposits.

The above methodology to determine the height of the ledge can be using for drilling machines, saw machines, diamond-rope and other technological equipment for exploitation of dimension stone quarries.

As criteria of technological parameters, optimizations are adopted: 1) the minimum economic unit costs ($C_з$) for the monolith separation from the rock mass; and 2) minimum loss block products ($\Sigma k_{втр}$) by means of maximizing the ratio of commodity blocks output (k_{bl}).

Rational monolith length L, width B values and the ledge well height is proposed to establish on the basis of the equations system solution:

$$
\begin{cases}
\dfrac{\left[\begin{array}{l} H_y^3\left[C_r\left(B(1-n)+L(1-n)\right)\right] - H_y^2 C_r BLn - \\ -H_y\left[C_n\left(B(1+n)+L(1+n)\right)\right] - C_n BL(n+2)\end{array}\right]}{LBH^{n+3}k_{np}} = 0; & (6) \\[2ex]
\dfrac{H_y^2 C_r + C_n}{L^2 H^{n+1} k_{np}} = 0; \qquad \dfrac{H_y^2 C_r + C_n}{B^2 H^{n+1} k_{np}} = 0.
\end{cases}
$$

where:

- C_n, C_r – the unit cutting stones cost, which include diamond-rope machine (EUR/h), electricity (EUR/kW·h) and diamonds in the instrument (EUR/carats),
- k_{pr} – proportionality coefficient (%),
- n – the indicator of blocking ($0.1 < n < 0.8$).

The dependence of the ledge well height and monolith size *L, B* is shown in **Figure 10**.

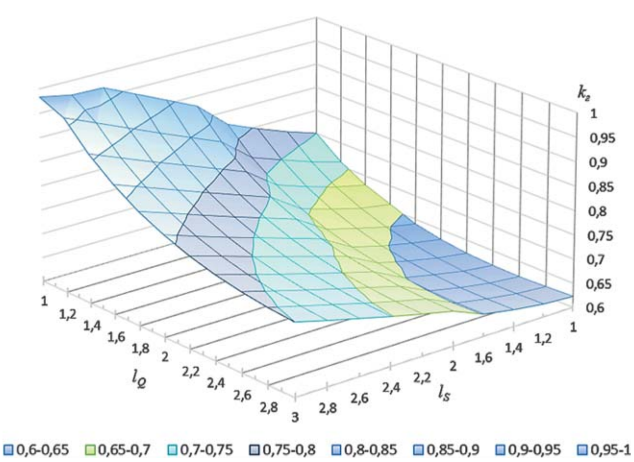

Figure 9: The geological dependence of the loss coefficient k_g from the distances between planes of the longitudinal l_S and transverse l_Q cracks systems

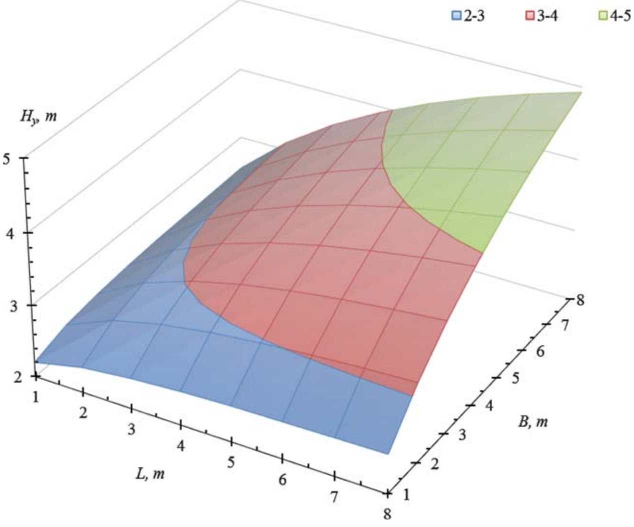

Figure 10: The dependence of rational ledge height from the monolith blocks size for category II ($V_{bl} > 3$ m³) at $n = 0{,}47$

Figure 10 allows to define rational height of the ledge for a particular field taking into account a stone block with the initial values of a specific crack array with the appropriate monolith dimensions. For mining and technical conditions of Natalyivske granodiorite deposit with specific cracks at one site in the quarry 2.1 m/m^2, according to the above procedure, the rational monolith dimensions are L = 6 m, B = 3 m, H_y = 3.4 m.

Set the equation for determining the rational values of the ledge heights, the criterion to minimize the block raw materials losses is $\Sigma k_{втр} \rightarrow$ min, which allows to increase commodity products output $k_{bl} \rightarrow$ max. For conditions of the Western section of the Natalievske deposit when $n_q = 2$, $n_s = 1$, $n_l = 1$, $l_q = 2.5$ m, $l_s = 2.7$ m, $l_l = 6.0$ m, $\alpha_q = 88^0$, $\alpha_s = 82^0$, $\alpha_l = 5^0$, $\gamma_{QL} = 83^0$, $\gamma_{QS} = 77^0$, $\gamma_{SL} = 65^0$, $d_{св} = 88$ mm, $\sigma_{сж} = 280$ MPa rational ledge height is 5.82 m. while the ledge height, taking into account only the distances between the rolling cracks, is 6.00 m, taking into account the angles of longitudinal cracks systems incidence H_y = 6.04 m, and taking into account the angles of transverse crack system incidence H_y = 6.56 m.

According to the above procedure, the obtained dependences $k_{втр}(L)$ and $k_{втр}(B)$, rational monolith length L and width B are defined according to the criterion of block raw materials losses minimization. Using data according to conditions of the Western section of the Natalyivske granodiorite deposit rational at the ledge, well height is 5.82 m, rational monolith width is established as B = 1.34 m and length as L = 5.0 m.

4. Conclusions

The optimization method of technological parameters at block stones production is developed. Realization of this method provides the improvement of block production quality. Effective parameters of jointed rock mass surface photogrammetry surveying while using digital non-metric cameras are proven to be rational.

A comparison of the results of specific fracture determination done directly using manual and remote measurements at the Natalyivske granodiorite deposit shows that precision in the remote method is higher (the error of specific fracture determination is 6 %).

To analyze the surface of the array, the developed application «Crack Detector» was used, which allowed for the analysis of the qualitative state of dimension stone rock mass, which further gives the possibility to predict the output blocks. To automate the calculation of the key indicators unit, in particular commercial unit volume, and mixing all of the above sections in a single form-blank, the application «Passport commodity block» was developed.

As a research result, taking into account the conditions of the Natalyivske granodiorite deposit, the rational ledge height is 5.82 m, which allows to ensure the required production of the quarry capacity, high mining equipment performance, mining safety, the minimum economic cost for a mining operation, low production cost and minimum block raw material losses.

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SAŽETAK

Optimizacija parametara tehnološkoga rudarstva u kamenolomu za poboljšanje kvalitete blokova arhitektonsko-građevnoga kamena na temelju fotogrametrijskih tehnika mjerenja

Istraživanje je usmjereno na obrasce promjena kvalitete proizvodnje blokova arhitektonsko-građevnoga kamena temeljeno na prethodnoj identifikaciji i mjerenju geometrijskih parametara prirodnih pukotina, modeliranju i planiranju konačnih dimenzija kamenih proizvoda i gotovih proizvoda s pomoću predloženih digitalnih fotogrametrijskih tehnika. Istražuju se optimalni parametri geodetskog mjerenja i procjenjuje se utjecaj mjerene udaljenosti na preciznost određivanja duljine i područja pukotina. Razmatraju se racionalni tehnološki parametri proizvodnje blokova arhitektonsko-građevnoga kamena.

Ključne riječi
arhitektonsko-građevni kamen, granitni blokovi, pukotine, istraživanje rudarstva, obrada slike, fotogrametrija

Author(s) contribution

Volodymyr Levytskyi: leader of the field investigations on all presented localities; analysed, synthesized and interpreted field and laboratory data; wrote the most of text of the article. **Ruslan Sobolevskyi:** participated in field investigations on all localities, providing guidelines for the manuscript. **Valentyn Korobiichuk:** collected data and analysed them for selection in this publication.