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Complex Photogrammetry Analysis of The Muck Pile Fragmentation Obtained in Russian Ore Mines

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The application of photogrammetry analysis in the evaluation of muck pile fragmentation of Russian diamond and copper-nickel ore mines was presented in the article. The evaluation was performed in the AutoCAD and Split Desktop 2.0 software based on the photographic documentation of three different muck piles. Moreover, calculation of Hazen's index which may be applied in Russia as an additional tool to evaluate blasting works were included. According to performed analysis, it can be observed that the weighted average grain diameters for Underground A and B were in the optimum range. Furthermore, Hazen's index shows that all analysed muck piles should be evaluated as non-homogenous. This could be explained by the type of exploitation system which was used during ore extraction.

Key words: *fragmentation, cumulative size distribution, sublevel caving, block caving mining, blasting works*

Introduction

One of the most important parameters which allow evaluating the quality of blasting works is the muck pile fragmentation. Proper evaluation of the muck pile fragmentation not only allows to examine the effectiveness of blasting works, but also affects the gravity movement of blasted ore during rock caving method, selection of loading, hauling and processing equipment, as well as the synchronization of the whole technical system at the mine (Biessikirski and Biessikirski, 2012; Sofranko et al., 2012; Sofranko et al., 2015; Terpák, 2010). Increased content of thick fractions in the loosened ore results in good movement of the material throughout the exhausted draw points, which positively affects the number of rock losses and ore dilution. In the case of a high number of oversized rocks, the exhausted draw points and grizzly level may be clogged or suspend by the broken ore (Terpák, 2016). Because of these observations, it can be stated that proper assessment of broken ore fragmentation should be made in order to validate blasting works or to make a necessary correction of blasting patterns or parameters.

Nowadays in order to assess muck pile fragmentation direct and indirect analysis is performed. Direct analysis (sieve analysis) is considered to be the most accurate method for evaluating actual fragmentation of the material, but given the amount of required material, time which is required to make the assessment and the economic factor, the method becomes less practical (Biessikirski, 2016a; Esen and Bilgin, 2010). On the other hand, indirect methods, including empirical methods, for example, Kuznetsov's and Cunningham's equation, as well as computer support in such methods as photogrammetry and laser technique, are widely used (Cunningham, 1983; Farmarzi et al., 2013; Kuznetsov, 1973; Krawczykowski et al., 2012). However, the photogrammetric and laser techniques are mainly used in opencast mining plants, and they have been the subject of numerous articles (Aler et al., 1996; Batko and Sołtys, 2007; Biessikirski et al., 2016a; Biessikirski et al., 2016b; Farmer et al., 1991; Maerz et al., 1987). In case of underground mining, the photometric technique was mainly used in studies on the influence of joint spacing on rock fragmentation under TBN cutter or numerical simulation of rock fragmentation mechanism subjected to wedge penetrations for TBMs (Li et al., 2016; Yin et al., 2016).

This paper aims to present the possible application of the photogrammetric method and Hazen's index to evaluate the fragmentation of broken ore in underground ore mines. Hazen's index is mainly applied in geotechnics, but it was also adopted in Russia as one of the factors of blast works evaluation.

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Characteristics of the exploitation system in an underground mine

The analysis of muck pile fragmentation was performed for two Russian ore mines (Underground mine A and Underground mine B) located on the Kola Peninsula, and a diamond mine (Underground mine C) located in Yakutia. Underground mine A and B are located at the Severny-Gluboky deposit. The northern part of the deposit is characterised by the Talnakh and Kharaclakh intrusion. Both intrusions show differences between the hanging wall and footwall of the fault (Lightfoot, 2017).

The extraction of copper-nickel ore (Ni å 0.48% in 1 ton of ore, Cuå 1.94% in 1 ton of ore) is conducted by sublevel caving (Fig. 1).

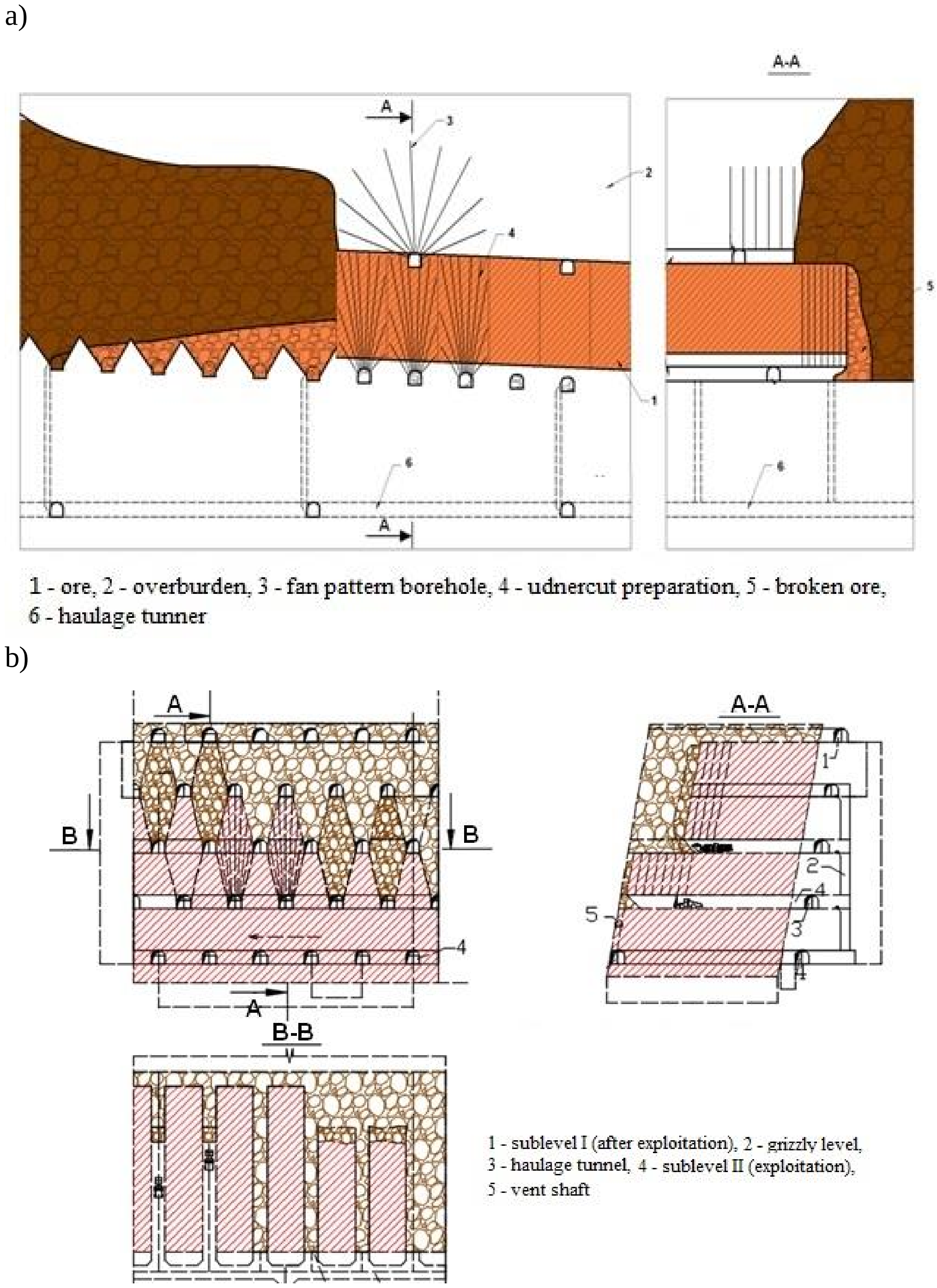


Fig. 1. Sublevel caving in a) Underground mine A, b) Underground mine B.

In Underground Mine A, the ore is extracted by block caving mining method (Fig.1a). The deposit is divided into undercut drifts. The height of the undercut drift depends on the bed thickness and varies from 18 to

50 m. An undercut with haulage is driven under the orebody with drawbells. Long boreholes were drilled in the fan pattern above the undercut. After the blasting, broken rocks were removed from the haulage access by loaders and haul trucks.

In Underground Mine B, the ore is extracted by the sublevel caving mining method (Fig.1b). Sublevel was developed in the ore body at regular vertical spacing. Blastholes around 30 m long were drilled from the access drifts in a ring pattern. The ore in the stope was blasted and collected in the draw-points. Blasting of each sublevel started at the hanging wall and mining then proceeded towards the footwall. As mining progressed downward, each new level was caved into the mine openings, with the ore materials being recovered while the rocks remained behind (Harraz, 2014). Loading was then continued until it was decided that waste dilution was too high (Fig. 1b).

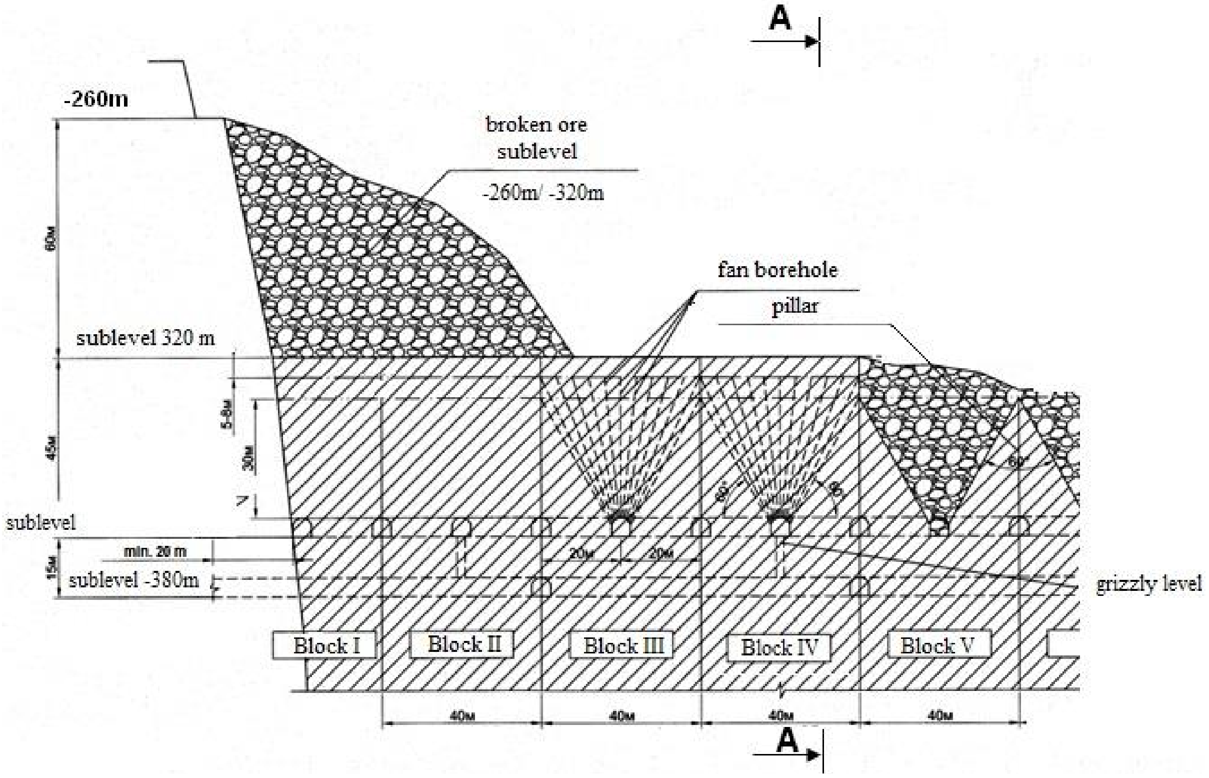


Fig. 2. Sublevel caving in a) Underground mine C.

In Underground Mine C (Fig. 2), diamonds are extracted from two adjacent kimberlite deposits by block caving mining method. Kimberlite deposits are located between limestones of the lower Ordovician. Diamonds are located in the eclogite deposit, which is in contact with peridot-dunite rocks. In 2010 the exploitation system was changed from open pit mining to underground mining.

Methodology

The evaluation of muck pile fragmentation was performed in the *AutoCAD* and *SPLIT Desktop* 2.0 software. The first stage of the analysis consisted of the preparation of photographic documentation in accordance with the recommendations described in (Aler et al., 1996; Batko and Soğlys, 2007; Farmarzi et al., 2013; Li et al., 2016). On the muck pile surface, an object with known dimensions was placed. In terms of *Auto CAD* analysis it was the SHSS-T rescue apparatus with a dimension of 111 × 146 × 248 mm, and in terms of *Split Software 2.0*, it was a ball with a diameter of 250 mm.

After the muck pile was scaled, manual delineation was made in *Auto CAD*. The manual delineation was presented in Fig. 3. The final stage of the process was to determine the broken rock diameter in accordance with the scaled object.

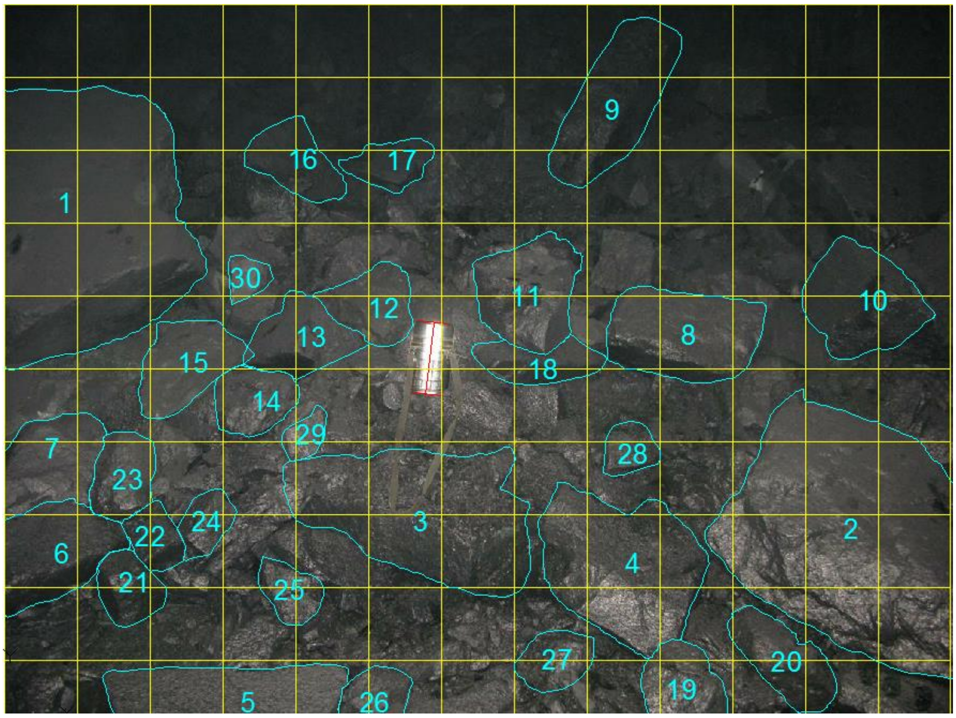
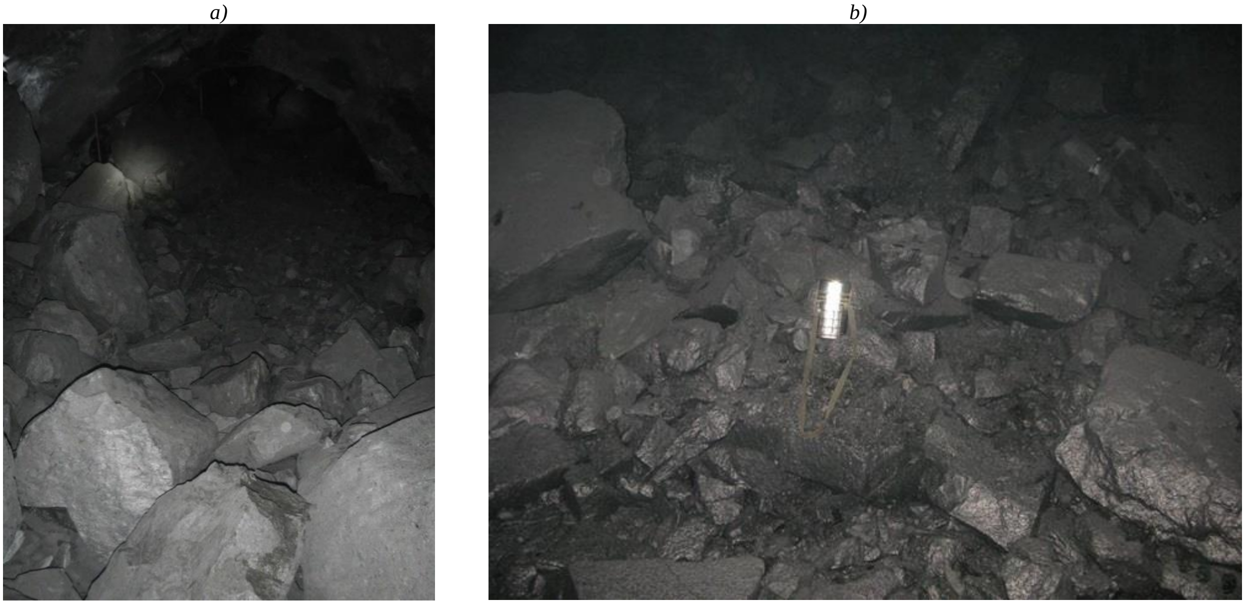


Fig. 3. Delineation in AutoCAD.

In the figure, it can be observed that the results obtained in the *Auto CAD* software were encumbered with a significant error. It was caused by a hinder delineation of the contour of the small rock. Further evaluation of the rock fragmentation is performed by the manual comparison of broken rock dimensions with scaled object dimensions. For the above reason, the exemplary results of the analysis were only presented for Underground Mine B.

The muck pile analysis obtained by the block caving mining method in three Russian underground mines was performed in the *Split Desktop 2.0.* software, in accordance with the methodology described in papers (Biessikirski et al., 2017a; Biessikirski et al., 2017b). An exemplary photos of evaluated muck piles were presented in Fig. 4a-c.


a)

b)

c)

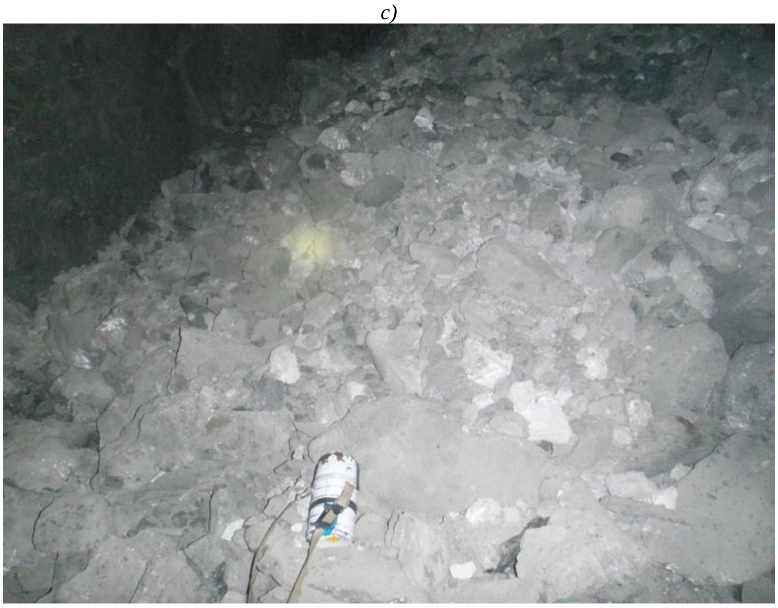
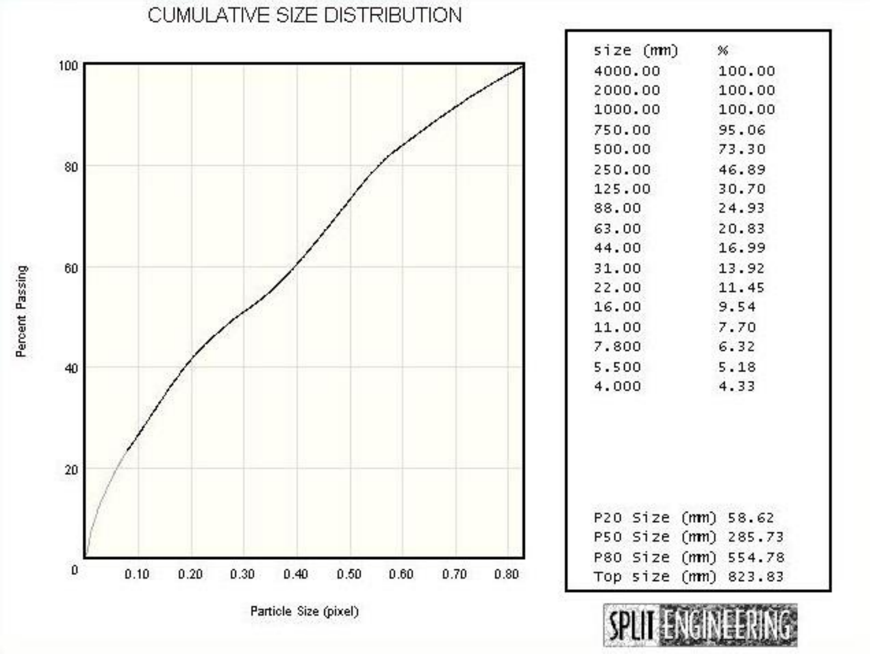


Fig. 4. Analysed muck pile: a) Underground mine A, b) Underground mine B, c) Underground mine C.

After delineation, the evaluation module was initiated by the user. The assessment of the broken rock fragmentation was made based on the Schumann distribution. As a result of the analysis, a logarithmic linear representation of the cumulative size distribution was obtained. An exemplary cumulative size distribution derived from the single muck pile analysis of the broken rock in underground mine A was presented in Fig. 5.



```
size (mm)      %
4000.00        100.00
2000.00        100.00
1000.00        100.00
750.00         95.06
500.00         73.30
250.00         46.89
125.00         30.70
88.00          24.93
63.00          20.83
44.00          16.99
31.00          13.92
22.00          11.45
16.00          9.54
11.00          7.70
7.800          6.32
5.500          5.18
4.000          4.33

P20 Size (mm) 58.62
P50 Size (mm) 285.73
P80 Size (mm) 554.78
Top size (mm) 823.83
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Fig. 5. Cumulative size distribution muck pile no. 1 series 1.

In Fig. 4, it can be observed that the number of oversized rocks (fractions above 700 mm) was ca. 4.94 %. The top size of the grain was ca. 823.83 mm. Furthermore, the fine particles (grains under 4.75 mm) were ca. 4.33 % (PN-B-02480: 1986).

Muck pile fragmentation analysis

An assessment of muck pile fragmentation was made for three different Russian underground mines. Each muck pile was analysed by *AutoCAD* and *Split Desktop 2.0* software, based on the three photographs which were taken from various points. The obtained results were then averaged and presented in Table 1 and Table 2. This resulted in obtaining singular cumulative size distribution, Fig. 6a and Fig. 6b. Detailed results obtained on the basis of *Split Desktop 2.0* software were presented in papers (Biessikirski et al., 2017a; Biessirski et al., 2017b).

Tab. 1. The average percentage of the output particle size based on AutoCAD software.

Grain size, [mm]	**An average amount of broken rock in the analysed muck pile** [%]
[mm]	**Underground Mine B** [%]
< 100	61.25
< 200	65.53
< 400	70.34
< 600	74.70
< 800	87.81
< 1000	100.00

Tab. 2. The average percentage of the output particle size based on Split Desktop 2.0 software.

Grain size [mm]	**An average amount of broken rocks in the analysed muck pile** [%]		
	Underground Mine A	**Underground Mine B**	**Underground Mine C**
< 4.00	2.84	10.30	2.13
< 5.50	3.33	11.14	2.69
< 7.80	4.00	12.07	3.32
< 11.00	4.82	13.25	4.13
< 16.00	5.93	14.80	5.26
< 22.00	7.12	16.42	6.48
< 31.00	8.72	18.57	8.14
< 44. 00	10.81	21.35	10.30
< 63.00	13.60	24.91	13.15
< 88.00	16.97	28.44	16.52
< 125.00	21.25	32.04	21.02
< 250.00	33.67	46.28	33.82
< 500.00	61.48	83.24	58.20
< 750.00	86.95	93.98	75.27
< 1000.00	98.88	97.73	87.55
< 2000.00	100.00	100.00	100.00

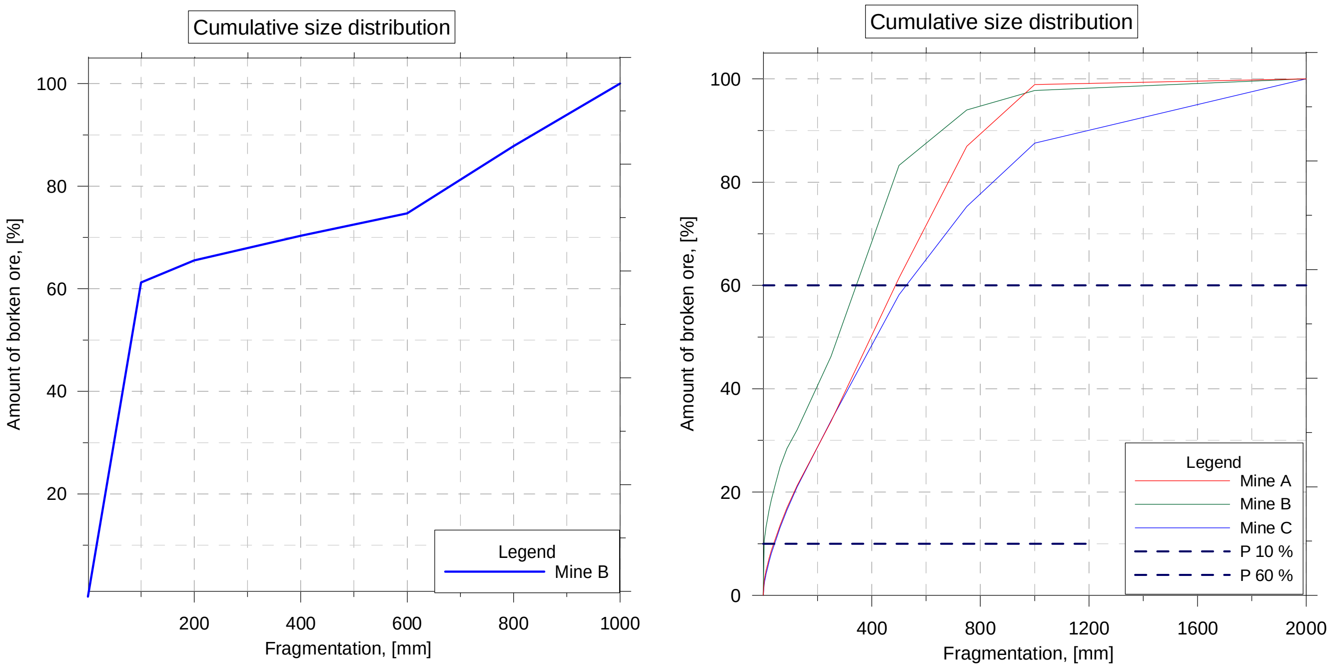

Fig 6. The cumulative size distribution: a) of each stage – Underground mine A; b) for the whole series – underground mine A; c) of each stage – Underground mine B; b) for the whole series – Underground mine B.

The results of muck pile fragmentation obtained in two different types of software were presented in Fig. 6a and Fig. 6b, and in Table 1 and Table 2. The differences between the results were caused by the limitation of the AutoCAD software during the delineation process. Because of this limitation, results obtained in the *AutoCAD* software should be treated only as cognitive. In further analysis, only the results obtained from *Split desktop 2.0* will be used.

According to the data, Fig. 6b and Table 2, it can be stated that cumulative size distributions obtained after the analysis of three different muck piles in three different underground mines are similar to each other.

Moreover, the average content of fines products was ca. 2.84 % (Underground mine A), 10.30 % (Underground mine B) and 2.13 % (Underground mine C), and the content of oversize rocks was ca. 13.05 % (Underground A), 6.02 % (Underground B) and 24.73 % (Underground C).

In Table 3 the average content of fragmented rock (w) in relation to its average grain size (a) in analysed muck pile was presented.

Tab. 3. The average percentage of the output particle size in relation to the average grain size.

Average grain size (*a*) [mm]	**The average percentage of the output particle size in relation to the average grain size (*w*),** [%]		
	Underground mine A	**Underground mine B**	**Underground mine C**
2.00	1.42	5.15	1.07
4.75	1.91	5.99	1.62
6.65	0.67	0.93	0.63
9.40	0.82	1.17	0.81
13.50	1.11	1.55	1.13
19.00	1.19	1.62	1.22
26.50	1.60	2.15	1.66
37.50	2.09	2.78	2.16
53.50	2.78	3.57	2.85
75.50	3.37	3.53	3.37
106.50	4.29	3.60	4.49
187.50	12.41	14.24	12.8
375.00	27.81	36.96	24.39
625.00	25.48	10.74	17.07
875.00	11.92	3.75	12.28
1500.00	1.12	2.27	12.45

Based on the data presented in Table 3, the weighted average of singular broken rock and Hazenôs index were determined.

Presented in Table 4, weighted averages of broken rock were determined according to Eq. 1.

$$x = \frac{a_1 \cdot w_1 + a_2 \cdot w_2 + \cdots + a_n \cdot w_n}{w_1 + w_2 + \cdots + w_n} \qquad (1)$$

where:

x - Weighted average of singular broken rock, Table 4

a_1, a_2, a_n - Average grain size, [mm], Table 3

w_1, w_2, w_n - The average percentage of the output particle size, [%], Table 3

Tab. 4. The average diameter of debris determined for the analysed underground mines.

The weighted average of singular broken rock (x)		
Underground mine A, [mm]	Underground mine B, [mm]	Underground mine C, [mm]
418.41	310.38	527.04

According to Table 4, it can be observed that the weighted average size of broken rocks was between 310.38 ÷ 527.04 mm. Due to the type of exploitation (sublevel caving method), it had been assumed that the optimum size of the material should be within the range of 300 ÷ 400 mm. It is undesirable to obtain a large number of broken rocks over 400 mm due to the possibility of rocks wedging in exhausted draw points. In the case of fines products, a high content thereof would be unfavourable, due to the possibility of excessive densification of broken rock material. According to Table 4 only in the case of Underground mine C the weighted average of broken rock size exceeded the optimum diameter. However, it should be noted that during the gravity movement of broken rock, wedging was not observed.

The detailed assessment of the muck pile was further made according to Hazenôs index (C_u), For example, 2. Hazenôs index is used in geotechnics, and it can be described as a grain size distribution with the permeability for effective diameter P60 and P10, Fig. 6. The high value of Hazenôs index indicates that soil is multi-fraction and the fine fractions will fill the voids between larger grains.

In some Russian underground ore mines, Hazenôs index has been adopted in order to evaluate the effect of blasting works. The assessment by Hazenôs index was performed based on the standard (GOST 25100: 2010), where it is assumed that muck pile with an index greater than 3 should be classified as non-homogeneous.

$$C_u - \frac{d_{60}}{d_{10}} \qquad (2)$$

where:

C_u - Hazenôs index

d_{10} - Effective diameter P10, Table 4
d_{60} - Effective diameter P60, Table 4

Tab. 5. Hazenôs index for the analysed mines.

Hazenôs index		
Underground mine A	Underground mine B	Underground mine C
12.42	88.24	12.47

Based on Hazenôs index, Table 5, it can be concluded that all analysed muck piles were non-homogeneous. Expected muck pile ought to be characterised as homogeneous or slightly non-homogenous. In practice, in case of blasting works and sublevel caving mining method, to obtain Hazenôs index equal or close to 3 is impossible. Therefore, the evaluated coefficients were correlated with the average content of fragmented rock in relation to its average grain size (Table 4), and a weighted average of broken rock for an individual underground mine. In Underground mine A, Hazenôs index was evaluated as 12.42 (Table 5), weighted average of broken rock was 418.41 mm (which exceeded the optimum diameter of broken rock: 300.00 $\div$ 400.00 mm), and average content of fragmented rock in relation to its average grain size indicated that domain fragmentation was within the range of 125.00 $\div$ 1000.00 mm. Similar results were obtained for Underground mine B (C_u = 88.24, x = 310.38 mm, with the dominant fragmentation within the range of 125.00 $\div$ 750.00 mm) and Underground mine C (C_u = 12.47, x = 527,07 mm, with the dominant fragmentation within the range of 250.00 $\div$ 2000.00 mm). Such a high value of Hazenôs index for Underground mine B can be explained by the significant presence of fines (a = 10.30% for the 4 mm fraction, Table 2) in the analysed muck pile. Moreover, in the case of Underground mine B, the weighted average size of broken rock slightly exceeds the lower value of the optimum range of fragmented material (300.00 $\div$ 400.00 mm). The high value of Hazenôs index and calculated the weighted average size of broken rocks indicate the necessity to make a proper correction of blasting work parameters in order to improve broken rock fragmentation.

It can be presumed that if the fractions that are the most dominant in the muck pile were the only ones to be considered (with less dominant fractions like fines or oversize rocks skipped in the analysis), the obtained values of Hazenôs index would be significantly decreased. In such a case, the calculated results for Underground mine A and Underground mine B would probably be close to 3.

Results

The performed analyses indicate the possible application of the photogrammetric technique for underground mining. However, the obtained results should be treated as an approximation due to the fact that photogrammetric techniques only yield information about the fragmentation of broken rock which is located only on the surface of the muck pile. In order to make a precise assessment of the indirect fragmentation evaluation by, i.e. multiple examinations of broken rock fragmentation in various muck pile cross sections should be performed.

The results obtained from the *AutoCAD* and *Split Desktop 2.0* software show differences. These were caused by the limitation of *AutoCAD* during the delineation process. The lack of possibility to make proper delineation of broken rock which had a small diameter and the necessity to make a manual assessment of fragmentation by comparing the dimensions of delineated broken rock with the dimensions of scaling object resulted in a significant error. For these reasons, it is recommended to use software specially designated for fragmentation assessment.

Obtained cumulative size distribution curves for particular underground mines were similar. However, in the case of Underground mine B the high amount of fines products (10.30%, Table 2, Table 3) was observed, and in the case of Underground mine C, the high amount of oversize rock (24.73%, Table 2, Table 3) was noticed.

Calculated weighted average size of broken rocks in Underground mines A and B was within the optimum range (300.00 $\div$ 400.00 mm). In the case of Underground mine, C the weighted average size of broken rocks exceeded the optimum values assumed by the mine authorities.

Calculated values of Hazenôs index indicate that analysed muck piles were non-homogeneous. This was caused by the type of exploitation system (blasting works and sublevel caving). Moreover, C_u for Underground mine B was determined as 88.24. Considering the evaluated weighted average size of broken rocks and dominant fragmentation of broken rocks the proper correction of blasting parameters should be made only in the case when similar results are obtained in the subsequent exploitation. In Underground mines A and C, the effect of blasting works was satisfactory. The exceeded value of the optimum broken rock diameter range in Underground mine C did not wedge the draw points during the gravity flow of broken rocks.

It can be presumed that if the most dominant amounts of fragmented rocks in relation to their average grain size were the only ones to be considered, then the determined value of C_u for Underground mines A and C would be close to 3. In terms of Underground mine B, the obtained value would be much lower than 88.24.

Moreover, it can be presumed that fines products would be moving gravitationally throughout the muck pile. However, in order to verify this statement, the abovementioned indirect type of analysis should be performed.

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