Statistical analysis of field measurements during the excavation of mine workings and their assessment

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Abstract. The article describes the production experience and a static analysis of the results of field measurements during the excavation of mine workings by contour blasting. A decision to perform field measurements during excavation and a statistical analysis of the results is made in order to assess the possibility of their use for normalization. The high degree of correspondence of the actual distribution of the results of field measurements to the normal law makes it possible to successfully use all the statistical characteristics of the theoretical distribution in analytical studies and in solving problems of improving technology and normalizing using the contour blasting method. The bulk of the results of downhole measurements of the parameters of contour blasting is in a narrow range of two standards $\bar{x} \pm S$, which allows us to further consider these ratios as criteria for the development of regulatory tolerances for the execution of a Blasting Pattern (BP) that provides practically acceptable contouring accuracy and the quality of the newly formed surface space.

1. Introduction

The use of the contour blasting method during underground mining leads to an increase in technical requirements for the accuracy of contouring and the quality of the newly formed contour surface, the parameters of which (contouring and surface roughness of the mined space) are determined by the accuracy of the design passport for drilling and blasting. However, in production conditions, the BP is usually implemented with significant deviations of the actual parameters from the calculated ones, which is caused by instrumental and methodological errors of surveying measurements when the axis and design loop are pulled to the bottom of the mine, the technical capabilities of the mining equipment used, structural and geological especially system of developed rocks, as well as organizational reasons that lead to significant violations of contour blast technology.

One of the ways to prevent technological disruptions is to regulate drilling operations in accordance with the regulatory tolerances for deviations from the calculated values for the placement parameters of contour holes. Moreover, the norms of deviations should take into account the real capabilities of the drilling equipment and the qualification level of the drills, therefore, normalization should be made on the basis of actual data on the parameters of the placement of holes and the resulting indicators of...
the efficiency of contour blasting. In this regard, it was decided to perform field measurements during the excavation of mine workings and to perform a statistical analysis of the results in order to assess the possibility of their use for normalization.

Explosive destruction of stressful media and the identification of patterns in this case are the subject of research by many scientists. A significant contribution to the study of the processes of rock destruction, the formation and propagation of stress waves in a rock mass during the explosion of explosive charges was made by: Adushkin V.V. [1], Borovikov V.A. [2], Zharikov I.F., Klochkov V.F. [3], Kryukov G.M. [4], Kutuzov B.N. [5], Rodionov V.N. [6], Menzhulin M.G. [7], Fokin V.A., Shemyakin E.I. [8], Hanukaev A.N. [9] and others.

2. Methods
At the first stage, for a quantitative assessment of the accuracy of the execution of the BP with respect to the design contour of the development, the following were carried out: corresponding downhole measurements of the main elements of the spatial location of the contour holes (113 examples). The drilling was carried out by the “Maximatic” drilling rig of the Tamrok company (Finland) without the use of automatic drilling tools and orienting holes in the direction. As a method of blasting, providing increased stability of exposures of rock masses by reducing the impact of an explosion on them, as well as obtaining flat walls of mine workings of a given profile and for relatively accurate observance of excavation contours and the safety of structures, the method of contour blasting was used.

3. Research results and discussion
In the course of work, 113 contour holes were drilled and the results of downhole measurements of the main elements of the spatial arrangement of contour holes (113 examples) are presented in Figure 1 and Table 1. Analysis of Table 1 showed that the studied parameters vary over a wide range relative to their calculated values. Only 24.8% of the examples fit into the recommended intervals for changing the deviation of the wellhead from the line of the design development contour \( C_0 = \pm 5 \text{ cm} \). A similar picture is observed in the change in the angle of inclination of the boreholes to the design surface of the mine, where 28.3% of the sample data are contained within its permissible values \( \phi = 2-4^\circ \). It is important to note that the total number of holes with a negative direction towards the worked out space was 23%. Such significant deviations of the indicated parameters from the permissible values of the calculated position of the contour holes have led to even greater limits of variability of the deviation of the bottom of the hole from the design of the output and contour bumps (range, respectively, 92 and 64 cm).

Figure 1. The results of downhole measurements of the parameters of the contour holes: 1 - line of the design contour of the development, 2 - actual contour, numerator - deviations of the mouth of the hole, substitute - deviation of the drill hole from the line of the design contour of the development.
Table 1. Static characteristics of the actual parameters of the spatial location of the contour holes during the excavation of underground mining.

| Characteristic | Distance between boreholes in a row, m | Deviation from the designed contour of a mine working, cm | The inclination angle of the borehole to the axis of the working, cm | Overkill, cm | Roughness Amplitude |
|----------------|---------------------------------------|----------------------------------------------------------|-----------------------------------------------------------------|-------------|-------------------|
| Parameter variation limits | 0.1-0.84 | -40-18 | -42-50 | -1.4-11.4 | -24-40 | -13-21 |
| Number of examples in excavation | 202 | 113 | 113 | 113 | 113 | 128 |
| Arithmetic Mean | 0.5 | -12.6 | -1.6 | -1.7 | 0.9 | 0.04 |
| Confidence Intervals Average | 0.48-0.52 | -14.7-10.5 | -4.7-1.5 | 1.2-2.2 | -1.2-3 | -1.4-1.5 |
| Sample variance $S^2$ | 0.015 | 129.1 | 272.2 | 7.8 | 132.4 | 68.1 |
| Standard deviation $x_S$ | 0.12 | 11.4 | 16.5 | 2.8 | 11.5 | 8.2 |
| Kolmogorov’s agreement criterion $\lambda$ | 0.48 | 0.075 | 0.018 | 0.082 | 0.194 | 1.40 |
| The probability of the implementation of the criterion $P(\lambda)$ | 0.965 | 1 | 1 | 1 | 1 | 0.178 |
| Interval value $-x\pm S_x$ | 0.38-0.63 | -24.12 | -18.1-14.9 | -0.5-4.5 | -10.5-12.4 | -8.2-8.3 |
| Sample size in the interval | 74.9 | 68.1 | 67.2 | 69.0 | 69.0 | 70.4 |

The degree of correspondence of the sample distribution to the normal theoretical one is determined by the condition $P(\lambda) >> 0.05$. Confidence intervals for the average are determined with a reliability of 0.9.

A high degree of variability was noted for all the studied parameters of the hole arrangement and the resulting blasting indices, which is characterized by standard deviations $S_x$ or coefficient of variation, except for the distance between the contour holes in the series, where $K_{var} = 24\%$; However, as evidenced by the values of the Kolmogorov criterion of agreement [10-12], the actual distribution of the results of downhole measurements in all cases corresponds to the normal theoretical one with high accuracy (Table 1), which indicates the random nature of these values and allows us to successfully use the laws of the normal distribution in the statistical study of the parameters of contour blasting.

It is noteworthy that the efficiency of contour blasting is estimated using the degree of smoothness of the walls and roof of a quarry, determined by the method based on the results of downhole measurements of roughness amplitude and edge gauges [13,14]. The degree of smoothness $P$, which is the ratio of the number of amplitudes whose values do not go beyond $a\pm 15$ cm ($a$-mean value), to the total number of measurements, in this case was 94% with a standard deviation of $S_a = 8.2$ cm $S_a \leq 9.1$ cm, which corresponds to the first smoothness category with a rating of “excellent.” The same indicator, calculated according to data on edge search, amounted to 85% at $S_\alpha = 11.5$ cm, $S_\alpha \leq 11.7$ cm, which corresponds to the second category of contouring quality with a rating of “very good”.

At first glance, such high rates of efficiency of contour blasting do not correspond to a significant scatter and other characteristics of the variability of the location parameters of contour charges. However, analyzing the data of the last column of the Table 1, it can be seen that 67-75% of the
primary results of measuring these parameters and the resulting quality indicators of contouring are grouped around their average values in a rather narrow range of their change, limited by the standard size \( \dot{x} \pm S \), which determines the quite satisfactory quality of the contouring of the workings. In this case, the average values of search and roughness amplitude are very small (0.9 and 0.04 cm) and actually correspond to the design contour of the mine; therefore, the considered interval \( \dot{x} \pm S \) and the content of primary data on the parameters of the placement of contour charges in it can be used as criteria in the development of regulatory requirements for the accuracy of the execution of the BP and normalization of borderline searches. Since the previously noted factors leading to disruptions in the technology of contour blasting at this stage of production development take place in any case, there is the Drilling and Blasting (D&B) when digging underground mines in rock formations, it can be concluded that the statistical characteristics considered for the spatial arrangement of contour holes as well as overflow sampling and roughness indicators are typical of the conditions of work, where drilling is carried out without the use of automatic means of drilling instrument [15].

However, such generalizations on the basis of the effectiveness indicators of the method of contour blasting require special mass measurements of overhead gauges in a wide range of mining conditions and the implementation of the corresponding estimated statistical analysis of the data obtained [16,17]. As a fundamental concept of rationing, we accepted the requirement of mutual compliance between regulatory tolerances for indicators of the geomechanical efficiency of blasting and for the downhole parameters of the spatial arrangement of contour charges, which provide the specified limitations of looping and roughness. Due to the significant scatter of the investigated technological parameters of contour blasting, they were compared with each other in order to identify the relationships, quantitatively assess the stability of the latter and determine the degree of influence of arguments factors on the overflow.

It was established that between the compared values there are correlation dependences characterized by a correlation coefficient \( r = 0.49-0.64 \) with a reliability of \( \mu = 6.7-11.3 \), which is significantly greater than the critical value \( \mu = 2.6 \) (Table 2, Figure 2) [10,18]. It is noteworthy that there is practically no connection between the magnitude of the overhead search and the angle of inclination of the holes to the axis of production, the comparison of which \( \hat{h} = h(\phi) \) characterized by low coefficients of correlation and determination (respectively, 0.042 and 0.02). A fairly stable correlation dependence is observed. the distance between the overhead \( \hat{h} \), the deviation of the drill hole from the projected development contour, corresponding to the regression line of the considered dependences, sm.

\[
\hat{h} = 2.1 + 0.35C_i
\]

\[
\hat{C}_i = -10 + 4.3\varphi
\]

where \( \hat{h}, \hat{C}_i \) are the overflows and the deviation of the drill hole from the projected development contour, corresponding to the regression line of the considered dependences, sm.

Of the correlation dependences presented in Table 2, equation (2) is characterized by the highest values of the correlation coefficients (0.64) and determination (0.41), indicating a high degree of influence of the angle of inclination of the borehole \( \varphi \) on the deviation \( \hat{C}_i \) which can also be seen from geometric constructions for a given value \( C_i = 0 \). Apparently, the correlation \( \hat{h} = h(\phi) \) exists in essence, but in this totality the results of downhole changes are not manifested.
### Table 2. Statistical characteristics of the correlation relationships between the spatial parameters of the contour holes.

| Statistical Characteristics | Correlation equation                                                                 |
|-----------------------------|---------------------------------------------------------------------------------------|
|                             | Correlation coefficient $r$                                                              |
|                             | 0.570                                                                                 |
|                             | Error in determining the correlation coefficient $\sigma_r$                           |
|                             | 0.056                                                                                 |
|                             | Reliability of the correlation coefficient $\mu$                                       |
|                             | 10.100                                                                                |
|                             | The standard deviation from the regression line $S_{n-2}$                             |
|                             | 10.300                                                                                |
|                             | Coefficient of determination $d$                                                       |
|                             | 0.302                                                                                 |
|                             | Sample size in the confidence zone of the regression line, %                          |
|                             | 31.000                                                                                |

$h$ overflow, cm; $C_0$ deviation of the mouth of the contour hole from the line of the design contour of the mine, cm; $C_1$ the same, deviation of the drill hole bottom, cm; $\varphi$ is the angle of inclination of the contour hole to the design surface of the mine, deg. The boundaries of the confidence zone in all cases are set with a probability of 0.99.

### Figure 2. Change in overhead $h$ depending on the deviation: a) 1 - the mouth of the hole $C_0$, 2 - of the bottom hole $C_1$, from the design development circuit (a) and the dependence of the deviations of the hole bottom $C_1$; b) 1 - the angle of inclination of the contour holes $\varphi$, 2 - the deviation of the mouth of the hole $C_0$ from the design output circuit (b).(solid lines are regression lines, dashed lines are the boundaries of the confidence zone with a probability of 0.99 for the corresponding regression lines).

Comparison of dependencies (1) and (2) with the equations:

\[
\hat{h} = 14 + 0.75C_0 \quad \text{(3)}
\]

\[
\hat{C}_1 = 8.3 + 0.8C_0 \quad \text{(4)}
\]

It has been shown that the change in the value of $C_1$ and the corresponding change in the search $\hat{h}$ in equation (1) are largely due to deviations of the mouth of the holes $C_0$ from the design development contour and the efficiency of the explosive breaking of the pre-contour layer, characterized by the utilization rate of contour holes, while the formula (2) does not at all take into account the interaction of the contour charge explosion with the surrounding rock mass.
Therefore, equation (1) and (2), despite the indirect relationship between \( h, C_t, \varphi \) and high stability indicators of the correlation, do not show the presence of the dependence \( \hat{h} = h(\varphi) \) and cannot be used to establish it by joint solutions. Thus, the foregoing makes it possible to exclude from further consideration the parameter \( C_t \) (deviation of the borehole from the design development loop) as not having a decisive influence on the effectiveness of contour blasting, as a result of which normalization is not practical.

To establish the joint effect of the argumentative parameters \( C_o \) and \( \varphi \) on the value of edge search, the multiple correlation method was used \[19,20\]. The following correlation equations are obtained:

\[
\hat{h} = 7.6 + 0.56C_o + 0.16\varphi \quad (5)
\]

or

\[
\hat{h} = 8.1 + 0.56C_o + 0.16\Delta\varphi \quad (6)
\]

here \( \Delta \) -deviations of the slope of the contour hole from its calculated technological value of 3 deg.

Dependences (5), (6) are characterized by a correlation coefficient of \( R = 0.55 \) with an error of its determination \( \sigma_R = \pm 0.065 \) with the reliability coefficient \( \mu = 8.38 \gg 2.6 \) (condition of stability of correlation). The coefficient of determination characterizing the proportion of variation of the value \( h \), due to the total influence of the deviation \( C_o \) and the angle \( \varphi \) is \( d = 0.302 \), that is at the level of values for the pair (univariate) dependences in the Table 2, which corresponds to the sample size within the confines of the confidence zone. The standard error allowed in determining the value of the law busting equations (5) and (6), depending on the studied factors is:

\[
\sigma_{dep} = \sigma_h \left(1 - R^2 \right)^{1/2} = \pm 9.6 \text{ cm},
\]

where \( \sigma_h \) - standard deviation for the bust (Table 1); \( R \) is the correlation coefficient for equations (5) and (6).

In contrast to the equation \( \hat{h} = h(\varphi) \), which has not received a specific expression due to the complete absence of correlation, the two-factor dependences (5) and (6) under consideration show a noticeable effect of the angle of inclination of the contour holes \( \varphi \) on the magnitude of the overflows when it changes in limits of technological deviations:

\[
\varphi_t + \Delta\varphi \geq \varphi > 0,
\]

where \( \varphi_t \) is the technological angle of inclination of the hole to the design surface of the mine \( \varphi_t = 3^\circ \), recommended deviation from the technological angle, \( \Delta\varphi = \pm 1^\circ \). From a comparison of the angular coefficients in equations (5) and (6), it follows that the influence of the tilt angle \( \varphi \) on the amount of enumeration in this case is 3.5 times less than the influence of the parameter \( C_o \). The analytical expression of the relationship of the studied parameters can be written as follows:

\[
h = C_o + L\eta \cdot \sin \varphi,
\]

where \( L \) is the depth of the contour hole, cm; \( \eta \) - utilization of holes. For the depth \( L = 3 \text{ m} \) and the coefficient \( \eta = 0.9 \) in the ideal case of blasting, formula (8) takes the form:

\[
h = C_o + 270 \sin \varphi,
\]

In order to visualize the joint influence of the studied factors on the overhead search, a graphical comparison of equations (5) and (9) in three-dimensional measurement was performed (Figure 3), where the argumentative parameters, in accordance with the recommendations, varied within the
limits: \(-5cm \leq C_0 \leq 5cm\) (relative to the designed contours of a mine working) and \(2^\circ \leq \varphi \leq 4^\circ\). The observed difference in the spatial position of the functional surfaces (correlation and theoretical) corresponding to equations (5) and (9) shows that the combined influence of the arguing factors \(C_0\) and \(\varphi\) on the amount of enumerations in expression (9) is significantly more intense than in the correlation dependence (5), graphically shown in Figure 3 by a hatched plane.

To quantify this effect, we compared the gradients of a plane-parallel scalar field characterizing the maximum rate of \(h = h(C_0, \varphi)\) change in the direction of the normal \(N_1\) and \(N_2\) to level lines 1.1 and 1.2 (Figure 3). So, at randomly selected points \(M_1\) and \(M_2\) the coordinates \(C_0 = 2\, cm\), \(\varphi = 3^\circ\), and \(h_z = 16.12\, cm\) the numerical values of the gradients were \(h_1 = \frac{N_1}{\text{grad}}, \, h_2 = \frac{N_2}{\text{grad}}\), respectively, at unit vectors \(i = lcm, \, j = 0.0174, \, K = lcm\). Thus, equation (9) reflects a more than ten-fold excess of intensity, changes in the function \(h_z = h_z(C_0, \varphi)\), in comparison with the correlation dependence (5) \(h^*_1 = h_1 \, C_0 \, \varphi\) which indicates a high degree of influence of the studied parameters on the resulting indicator of the effectiveness of contour blasting \(h\).

Calculations under the conditions \(C_0 = \text{const}\); \(\varphi = 2^\circ\); \(\varphi = 4^\circ\) (I) and \(\varphi = \text{const}\), \(C_0 = -2\, cm\); \(C_0 = +2\, cm\) (II) showed a significantly more intense influence of the angle of inclination of the contour holes on the enumerations, in comparison with the deviation of the mouth of the hole \(C_0\) especially in the field of equation (9), where the degree of influence of the angle \(\varphi\) (\(\Delta h\) at \(C_0 = \text{const}\)) is 30 times greater than the increment \(\Delta h\) according to equation (5). Similar comparisons of the calculation results according to condition II are characterized only by a twofold excess of the degree of influence \(C_0\) (\(\Delta h\) at \(C_0 = \text{const}\)) in the compared formulas (9) and (5).

4. Conclusion

The results of the studies allow us to draw the following conclusions:

1. The actual scatter of the location parameters of the contour boreholes and the corresponding borderline bumps, as well as the statistical stability characteristics of these quantities are typical technological features of D&B without the use of automatic means for monitoring the drilling of boreholes during mine workings in the conditions of domestic mining construction;

2. Deviation of the borehole bottom from the design contour of the mine, being a function of the angle of inclination of the borehole to the axis of the mine, does not in itself determine the effectiveness of contour blasting, and therefore its use as a standard when controlling the destructive effect of the explosion is not practical;
3. The high degree of correspondence of the actual distribution of the results of field measurements to the normal law $P(\lambda) \approx 1$ makes it possible to successfully use all the statistical characteristics of the theoretical distribution in analytical studies and in solving problems of improving the technique and normalizing using blasting method;

4. The bulk of the results of downhole measurements of the parameters of contour blasting (68-75%) is in a narrow range of two standards $x \pm S$, which allows us to further consider these ratios as criteria for the development of regulatory tolerances for the execution of BP providing almost acceptable contouring accuracy and quality of the newly formed surface of the worked out space;

5. The angle of inclination of the contour holes has a significantly higher degree of influence on the enumerations, in comparison with the deviation of the mouth of the holes from the design contour of the output (within the practically acceptable value of the coefficient of boreholes use contour charges).

References
[1] Adushkin B B 1998 Model studies of rock destruction by explosion Collection "Physical problems of rock destruction." (Moscow IPKON RAS) pp 18-29
[2] Borovikov V A and Vanyagin I F 1985 Technique and technology of blasting (Leningrad: LGI) p 175
[3] Klochkov V F 1976 The dependence of the specific consumption of explosives on mining factors Mountain Journal 5 37–48
[4] Kryukov G M 2006 The physics of explosive destruction (Moscow) p 275
[5] Kutuzov B N 1994 Rock destruction by explosion Explosive technologies in industry (Moscow: MGI) p 448
[6] Radionov V N 1971 The mechanical effect of an underground explosion (Moscow: Nedra) p 312
[7] Menzhulin M G, Paramonov G P, Mironov Y A and Yurovskikh A B 2001 Method for calculating the additional destruction of rocks at the quasistatic stage of the explosion Notes of the Mining Institute (Saint-Petersburg) 148 (1) 43–47
[8] Shemyakin E I 1963 On the waves of stresses in strong rocks Applied Mechanics and Technical Physics 5 83–93
[9] Hanukaev A N 1979 Reducing the tension of the rock mass using explosions (Moscow: Nauka) p 120
[10] 1966 Design and construction of large dams. Underground work and the improvement of the rocky foundations of dams Based on the materials of the VII and VIII international congresses on large platinum (Moscow: Energy Publishing House)
[11] Shekhurdin V K, Nesmotelov V I and Fedorenko P I 1987 Mining (Moscow: Nedra) p 440
[12] Brylov S A, Grabchak L G and Komosenken V I 1989 Mining and drilling and blasting operations (Moscow: Nedra) p 287
[13] Khasanov N M, Suleymanova M A and Yakubov A O 2018 Stability of the hydraulic tunnel of the Nurek hydroelectric station under seismic impact Polytechnic Bulletin 1 (41) 276–284
[14] Baron L I and Klyuchnikov A V 1967 Contour blasting during sinking of workings (Leningrad: Nauka) p 203
[15] Khasanov N M and Yatimov U A 2018 Geological factors affecting the destruction of the stability of hydraulic tunnels Bulletin of KSUSTA (Bishkek) 2 (60) 94–98
[16] Bulychev N S 1982 Mechanics of underground structures (Moscow: Nedra) p 270
[17] Ryzhov P A 1973 Mathematical statics in mining (Moscow: Higher School) p 283
[18] Lishin G A and Geimon L M 2000 Blasting by the method of smooth blasting Mine construction number (Moscow) 2 160–183
[19] Baron L I, Turgonikov I A and Klyuchnikov A V 2005 Violation of rocks during blasting (Moscow) p 176
[20] Brotanek I 1983 Contour blasting in mining and construction (Moscow: Nedra) p 182