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Influence of the orientation of elongated shaped charges on the design of an optimal borehole pattern for the Kryvyi Rih Basin

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Abstract. The relevance of this study is driven by the need to improve the efficiency of drilling and blasting operations at iron ore open-pit mines in the Kryvyi Rih Basin through the application of elongated shaped charges spatially adapted to the structural characteristics of the rock mass in order to optimise borehole pattern parameters. The aim of the study was to determine the influence of the spatial orientation of elongated shaped charges on the geometric parameters of the borehole pattern and to develop engineering recommendations for its optimal design under the complex mining and geological conditions of surface mining. The research methodology was based on an integrated approach combining numerical modelling of wave propagation in continuous media using constitutive material behaviour models with nonlinear mathematical optimisation based on the Generalised Reduced Gradient (GRG) algorithm. The results demonstrated a nonlinear relationship between the dimensions of the intensive fragmentation zone and the rotation angle of the shaped cavity. Statistical analysis confirmed that the optimum rotation angle is 45°, provided that the shaped charge jet is oriented parallel to the strike of the principal fractures. Under these conditions, an elongated elliptical fracture zone is formed, enabling the transition from conventional square borehole patterns to rectangular spatial layouts. It was established that this configuration allows the spacing between boreholes to be increased to 7 m, while achieving a borehole convergence coefficient

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of 1.52. Conversely, orienting the charge perpendicular to the fracture system produces an acoustic shielding effect, restricting the propagation of explosive energy and limiting the expansion of the borehole pattern. The practical significance of the study lies in the development of a differentiated methodology for the spatial positioning of explosive charges in ferruginous quartzites. The implementation of the proposed optimised borehole pattern parameters reduces specific drilling costs by 33% without compromising fragmentation quality. Furthermore, it decreases drilling tool wear, shortens the preparation cycle, and proportionally reduces the environmental impact through lower dust and gas emissions

Keywords: shaped cavity; ferruginous quartzite fragmentation; dynamic modelling; borehole convergence; drilling and blasting operations

Introduction

The efficiency of open-pit mining operations was largely determined by the quality of drilling and blasting preparation of the rock mass. One of the promising directions for intensifying the destruction processes was the application of elongated shaped charges (ESCs), capable of concentrating explosion energy in a specified direction. Globally, research on directed explosive action was actively developed, and increasing the efficiency of rock mass destruction through the directed concentration of detonation energy was considered one of the most urgent scientific and practical tasks for the modern mining industry.

The analysis of the current state of research in this field indicated significant interest from the scientific community in this issue. Furthermore, attention was focused on the mathematical and mechanical modelling of the stress field during an explosion by Q. Gao *et al.* (2020). In that study, the influence of the detonator's location on the efficiency of bench blasting was examined, and it was concluded that the correct spatial localisation of initiation was critically important. According to Y. Yao *et al.* (2021), an innovative approach using a bilateral slotted shaped charge was developed and investigated. The advantages of microsecond delays for the formation of directed cracks between boreholes were proven. Significant attention was also paid to the optimisation of the charge design itself. For instance, various shapes of shaped charge liners were investigated by K. Liu *et al.* (2023). Based on experimental data, it was concluded that the liner shape was the determining factor for the efficiency of directed rock destruction.

Despite significant progress in this field, the majority of research was focused on general principles, without proper adaptation to the specific mining and geological conditions of the iron ore open-pit mines in the Kryvyi Rih basin. The issue of mass blasts in the Kryvbas open-pit mines was studied by Ye.O. Nesmashnyi *et al.* (2022), whilst developing a method for the rapid determination of the flyrock distance. It was concluded that blast parameters required strict control to ensure safety. The variability of drilling and blasting parameters at local enterprises was analysed by H. Yeremenko *et al.* (2022). According to those researchers, there was an urgent need to improve the borehole pattern parameters, taking into account the spatial orientation of elongated shaped charges, to increase the quality of fragmentation and reduce the yield of oversized blocks.

A study by B. Andrieiev *et al.* (2026) was dedicated to a detailed analysis of the physical, mechanical, and hydrodynamic processes accompanying the detonation of elongated shaped charges during rock mass destruction under the conditions of iron ore open-pit mines. Attention was focused on the mechanisms of formation and interaction of shaped charge jets with high-strength ferruginous quartzites and ores. The redistribution of explosion energy during the application of the shaped charge effect was substantiated in the work, which allowed achieving directed crack formation and improving the quality of rock mass fragmentation. The scientific value of the study consisted in establishing the patterns of shock wave propagation and dynamic stresses in the rock mass upon detonation of elongated shaped cavities.

Consequently, the issue of developing scientifically substantiated methods for the optimal design of the borehole pattern, which would take into account the influence of ESC orientation on the efficiency of explosive breaking under the conditions of the Kryvyi Rih basin, remained unresolved. Within the scope of the conducted research, the aim was to determine the patterns describing the impact of the spatial orientation of elongated shaped charges on the formation of the borehole pattern, in order to create practical tools for its optimal design in the open-pit mines of the Kryvyi Rih basin. The realisation of the set objective encompassed the solution of three key tasks. Initially, global experience and theoretical foundations of using shaped charges for directed rock destruction were analysed. The subsequent step involved the construction of a mathematical model and the conduction of experimental studies on the influence of the ESC spatial orientation on fragmentation quality under the conditions of the Kryvyi Rih basin open-pit mines. The final stage of the work was the development and verification of a practical engineering methodology for calculating borehole pattern parameters.

Literature Review

The issue of increasing the efficiency of drilling and blasting operations was the subject of constant attention from researchers. A significant contribution to the development of the theory and practice of explosive rock destruction using shaped charges was made by various researchers. The influence of the design features of shaped charge liners on the nature of rock destruction was investigated by K. Liu *et al.* (2023) based on numerical modelling and laboratory experiments. Flat, arc-shaped, and triangular shapes of cavities were compared with each other. Based on the results of the work, it was concluded that the application of a triangular-shaped liner provided the best directed effect compared to other analogues.

According to Y. Yao *et al*. (2021), an innovative approach using a bilateral slotted shaped charge (BGSSC) was developed. The impact of microsecond initiation delays on the dynamics of crack development was investigated. It was concluded that precisely calculated time intervals allowed the formation of through cracks between boreholes, providing an even separation plane. The application of directed controlled blasting technology during the excavation of unstable rock slopes along the Konkan Railway was investigated by N. Bhagat *et al*. (2020). It was concluded that the proposed technology provided better control of the excavation contour, increased slope stability, and reduced undesirable rock destruction. The influence of the eccentric placement of a decoupled charge on the nature of rock destruction was investigated by C. Pan *et al*. (2022) using numerical modelling. It was established that such a design contributed to the concentration of explosion energy in a specified direction and improved the controllability of the destruction process. A numerical model based on the particle-based numerical manifold method for modelling crack development during explosive rock destruction was developed by X. Li *et al*. (2017). It was confirmed that the proposed approach reliably reproduced the crack propagation process and could be used for the optimisation of drilling and blasting parameters. The features of rock destruction when using a slotted cartridge with a decoupled charge were investigated by Y. Wang (2017). The results demonstrated that such a design provided a more efficient direction of explosion energy and the formation of controlled cracks. The mechanism of crack formation during shaped charge blasting was investigated, and a novel dual shaped charge technology was proposed by P. Xu *et al*. (2024). It was established that the use of two shaped charges increased the efficiency of directed rock destruction and improved the control of crack development. The mechanism of directed rock splitting under the action of a shaped charge jet was investigated by D. Liu *et al*. (2023). It was concluded that the shaped charge jet provided energy concentration in a specified direction, which facilitated the formation of main cracks and increased the efficiency of directed blasting.

A study by Q. Gao *et al*. (2020) was dedicated to the mathematical and mechanical analysis of stress field formation in an explosive charge. The main object of the research was the influence of the detonator's location on the overall explosion energy. It was concluded that the optimisation of the charge initiation point was capable of fundamentally changing the spatial distribution of energy and significantly improving the efficiency of bench blasting. Environmental and resource-saving aspects of blasting operations in open-pit mines were investigated in a study by O. Tverda *et al*. (2021). A new charge design with a radial gap completely filled with a chemically active substance was developed. It was concluded that such an approach allowed not only to reduce the seismic pressure on the rock mass but also to effectively neutralise harmful gases formed after detonation. The direct issue of designing and conducting drilling and blasting operations under the specific conditions of the Kryvyi Rih iron ore basin was also a subject of active research. Experimental studies on the variability of drilling and blasting parameters at the "Pivdennyi" open-pit mine of "Rudomain" LLC were conducted by H. Yeremenko *et al*. (2022). The impact of new materials on the final particle size distribution of the blasted ore was studied. Based on the results of the work, it was concluded that there was a necessity for the constant adaptation of borehole pattern parameters to the changing mining and geological conditions of the deposit.

It should be noted that despite the significant volume and depth of the aforementioned research, there were aspects of the topic to which insufficient attention was paid. In particular, the quantitative impact of the specific spatial orientation (angle of rotation) of elongated shaped charges on the rational distance between boreholes in the rock mass was practically unexplored in the analysed works. The absence of clear mathematical dependencies and a differentiated approach to the optimal design of the borehole pattern, taking into account the direction of the ESC action under the specific conditions of the iron ore open-pit mines of the Kryvyi Rih basin, formed a scientific gap, which served as the main prerequisite for conducting this research.

Materials and Methods

The general strategy of this research was based on a complex multiscale approach, which organically combined the analytical substantiation of gas-dynamic processes in the near-blast zone and the multivariant computer modelling of nonlinear continuum mechanics. Such a symbiosis of methods allowed overcoming the conceptual insufficiency of purely empirical or exclusively numerical approaches, verifying theoretical hypotheses regarding the spatial anisotropy of the stress-strain state of the rock mass caused by the directed action of the explosion, and obtaining reliable data for the further macroscale optimisation of drilling and blasting parameters. The limitation of this study was that the patterns of the formation of elliptical destruction zones were established for the conditions of hard ferruginous quartzites (f = 16 – 18). Changes in the properties of the rock mass or types of explosives would require further comparative analysis and calibration of mathematical models at other deposits.

The research logic involved a sequential transition from the micromodelling of shaped charge wave effects to the macroscopic engineering calculations of the geometric configurations of the borehole pattern. The mathematical and physical bridge in this transition was the energy focusing efficiency coefficient, obtained through the polynomial approximation of the volumes of the destroyed medium based on the results of a series of numerical calculations. The application of polynomial approximation in this context was a method of justified data dimensionality reduction, which allowed transforming redundant arrays of discrete parameters of the stress-strain state into a continuous analytical function. Since the volume of destruction was selected as an integral criterion accumulating energy expenditures on deformation, crack formation, and wave interference, the obtained polynomial dependence acted as a normalised response function of the geomedium. This allowed collapsing microscale dynamic effects into a weight coefficient, which was directly integrated into classical engineering methodologies for calculating blasting operations, ensuring the accurate transfer of fundamental patterns into applied design algorithms.

The experimental base of the research was formed with deep consideration of the specifics of the physical and mechanical properties of typical rocks of the Kryvyi Rih iron ore basin under conditions of intensive deepening of mining operations, where high tectonic stresses and changes in the nature of destruction began to play a dominant role. Unweathered primary magnetite quartzites of the basin's mine administrations were selected as the main media for studying the processes of fragmentation intensification. Magnetite quartzites were characterised by extremely high strength (strength coefficient on the M.M. Protodiakonov scale $f = 14 \div 18$, compressive strength $\sigma_c = 180 \div 220$ MPa, dynamic tensile strength $\sigma_t = 14 \div 18$ MPa), high density ($\gamma = 3{,}200 \div 3{,}400$ kg/m^3) and significant acoustic stiffness ($Z \approx 14 \div 16 \cdot 10^6$ kg/(m$^2 \cdot$ s)). The critical geomechanical feature of these ores was their structural anisotropy, caused by the complex folded block structure and the spatial orientation of the main systems of natural macrocracks. The presence of a network of subvertical and subhorizontal cracks with a distance between them from 0.2 to 0.8 m led to the spatial variability of the ultimate strength and a difference in the propagation velocity of elastic stress waves along and across the strike of the rock mass of up to 15-20%. Ferruginous quartzites of a schistose texture, as less strong host rocks, possessed a strength of $f = 8 \div 10$ (compressive strength $80 \div 120$ MPa, density $\gamma = 2{,}700 \div 2{,}900$ kg/m^3)). This texture formed an extremely high degree of mechanical and acoustic anisotropy (the structural anisotropy coefficient reached 1.4-1.6), which caused intensive dissipation of the kinetic explosion energy on the planes of weakness and required precise spatial alignment of the shaped charge axis with the dominant anisotropy vectors of the medium. This aspect was spatially formalised through the introduction of the azimuthal angle β, which determined the orientation of the shaped charge plane in the plan relative to the dominant system of natural cracks in the rock mass, which was a necessary condition for preventing energy losses. To initiate directed destruction and overcome the isotropic nature of the expansion of detonation products, specially designed elongated shaped charges were used, the structural diagram of which was presented in Figure 1.

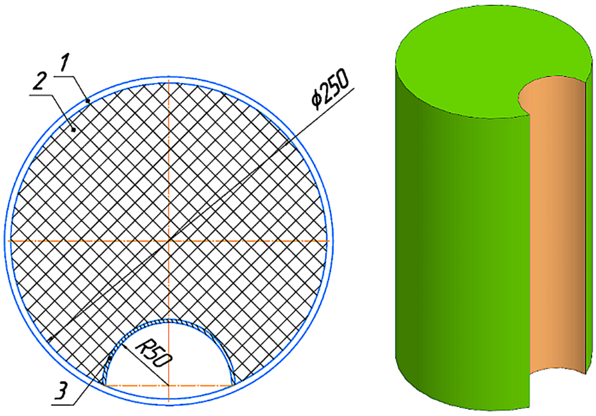

Figure 1. Cross-section of the elongated shaped charge
Notes: 1 – polymer shell; 2 – explosive; 3 – shaped cavity
Source: developed by the authors

According to the drawing, the total diameter of the charge (item 1) was 250 mm, which fully corresponded to the typical diameters of blast holes in Kryvbas open-pit mines when heavy roller cone drilling rigs of the SBSH-250 type were applied, which ensured the technological efficiency of implementation. The charge shell was manufactured from an extruded polymer material with a thickness of 2-3 mm. The choice of polymer was determined by its acoustic impedance, which was close to the parameters of industrial explosives, which minimised parasitic wave reflection at the media interface, and also provided the necessary geometric stability of the structure during loading into water-filled boreholes. The internal space (item 2) was filled with a pourable industrial explosive, for example, a water-resistant emulsion composition of the "Ukrainit" type with a linear density of about 40-45 kg/m. Along the charge formation line over its entire length, a semi-cylindrical shaped cavity (item 3) with a radius of 50 mm (R50) was formed. The choice of the semi-cylindrical geometry was determined by the necessity of forming not a classical thin shaped charge jet with high penetrating ability (the Munroe effect), but a massive explosively formed projectile with a flat front, capable of transmitting the maximum impulse of tensile stresses to the rock mass. Exclusively an air gap or a thin polyvinyl chloride film for waterproofing was used as the liner of the shaped cut. The rejection of the traditional metal liner was associated with the need to prevent the loss of detonation thermal energy on the plastic deformation of the metal and melting, focusing exclusively the gas-dynamic flow onto the borehole wall. The length of one charge module was 1-2 metres, with the structural possibility of their rigid axial connection by means of couplings into a continuous charge column of any required length.

To investigate the complex wave pattern, gas-dynamic shock parameters, and the initial stage of the micro- and macrocracking zone formation, a computer modelling methodology was applied in the high-performance ANSYS Autodyn software package, using the explicit method of integrating continuum dynamics equations over time. The computational domain was discretised by a detailed hexahedral finite-element mesh using a coupled formulation (Euler-Lagrange). In this setup, detonation products and the air medium were described by an Eulerian mesh to avoid problems with element degeneration under large gas deformations, and the rock mass was described by a Lagrangian mesh with built-in algorithms for geometric erosion of elements upon reaching critical values of plastic deformations or instantaneous destruction. The detonation of the explosive was modelled using the phenomenological Jones-Wilkins-Lee (JWL) equation of state, the parameters of which (A, B, R_1, R_2, ω, E_0) were precisely calibrated for emulsion explosives based on copper cylinder expansion tests. The behaviour of the rock mass under intensive dynamic loading was described by the complex Riedel-Hiermaier-Thoma (RHT) constitutive model. This model was critically important for the reliable reproduction of the behaviour of brittle media, since it took into account not only rock strength degradation due to the gradual accumulation of damage (parameter D), but also the nonlinear dependence of the yield strength on hydrostatic pressure, strengthening effects at high strain rates, and the influence of the Lode angle on the yield surface shape. Non-reflecting boundary conditions were set at the external boundaries of the computational domain to simulate an infinite rock half-space and level out errors from stress wave reflections from the artificial boundaries of the computational domain. A mesh sensitivity analysis was conducted until the convergence of results for peak pressures at the shock wave front with an error of less than 5% was achieved.

Since the direct search for optimal borehole pattern parameters by finite element methods at the level of the entire open-pit block was computationally impossible due to the gigantic number of degrees of freedom and the difference in scales (from millimetres in the borehole to tens of metres in the bench), the optimisation task was formalised in the form of a strict macroscale mathematical model of nonlinear programming (NLP). The general problem statement included an objective function of reduced economic costs and a complex system of nonlinear technological and geometric constraints:

$$F(X) = C_d \cdot (H + L_p) + C_e \cdot Q_a \cdot W \cdot H \cdot \gamma \to min$$
$$\begin{cases} A_0 \cdot K_f(\theta) \cdot \frac{a \cdot W \cdot H}{Q^{0.8}} \cdot Q^{1/6} - [d_{max}] \le 0 \\ K_s \cdot R \cdot Q^{-\alpha} \cdot K_{ppv}(\theta) - [PPV_{kr}] \le 0 \\ a_{min} \le a \le a_{max} \\ W_{min} \le W \le W_{max} \\ L_{p,min} \le L_p \le L_{p,max} \\ 0 \le \theta \le \frac{\pi}{2} \end{cases}, \quad (1)$$

where C_d – the average cost of drilling one running metre of a borehole in hard quartzites; H – the height of the working bench; C_e – the cost of one kilogram of the manufactured explosive; Q_a – the design specific consumption; γ – the rock density. In the presented mathematical model, the following vector acted as the controlled vector of independent spatial variables:

$$X = [a, W, L_p, \theta, \beta]^T, \quad (2)$$

where a – the distance between boreholes in a row; W – the line of least resistance (distance between rows); – the amount of subdrilling (which directly affected the toe breakage). The spatial orientation of the charge was described by two parameters: θ – the zenith angle of the shaped charge axis relative to the exposed plane in the vertical section (visualised in Fig. 2 as angle α); and β – the azimuthal angle of jet orientation in the horizontal plane relative to the strike of the dominant system of tectonic macrocracks.

The objective function $F(X)$ represented a mathematical expression for the minimisation of the total reduced costs for the basic processes of drilling and blasting operations. The first and most important inequality of the system formalised the critical technological condition for ensuring the required quality of rock mass fragmentation: it was the empirical Kuz-Ram equation, modified by the introduction of the surrogate energy focusing efficiency coefficient K_f (θ, β). The transition from microscale wave modelling in ANSYS Autodyn to macroscale optimisation calculation was realised through a sequential procedure of constructing a surrogate model (metamodel) based on interconnected stages. Initially, relying on a series of 45 basic numerical calculations in Autodyn for discrete spatial combinations of the zenith θ_i and azimuthal β_j angles, a step-by-step calculation of the degradation and strength fields of the rock mass was performed. In the subsequent step, the volume of the effective destruction V_{frac} (θ, β) zone was determined by numerical three-dimensional integration of those elements of the rock Lagrangian mesh for which the accumulated damage index in the RHT model reached the critical value $D \geqslant 0.85$, which corresponded to the complete exhaustion of the medium's bearing capacity and disintegration into separate fractions. Following this, the calculation of the normalised dimensionless energy focusing indicator relative to the baseline explosion of a cylindrical charge of similar mass without a shaped cavity (isotropic standard) was carried out as a ratio $\bar{V}_{frac}(\theta, \beta) = V_{frac}(\theta, \beta)/V_{iso}$. At the final stage, the obtained discrete data array $\bar{V}_{frac}$ (θ_i, β_j) was approximated by a two-dimensional third-degree polynomial using the least squares method (LSM), which allowed obtaining the analytical expression of the coefficient as a smooth and differentiable function:

$$K_f(\theta, \beta) = c_0 + c_1\theta + c_2\beta + c_3\theta^2 + c_4\theta\beta + c_5\beta^2 + \\ + c_6\theta^3 + c_7\theta^2\beta + c_8\theta\beta^2 + c_9\beta^3, \qquad (3)$$

where $c_0 \ldots c_9$ – empirical approximation coefficients calculated for a specific rock type. In particular, for magnetite quartzites, the values $c_0 = 1.08$, $c_1 = -0.32$, $c_2 = 0.54$, etc., were obtained, while ensuring a high quality of agreement with the coefficient of determination $R_2 = 0.94$. Due to the representation of the coefficient K_f (θ, β) in the form of a smooth polynomial, the GRG optimisation algorithm gained the capability of continuous calculation of the objective function and constraint gradients during the search for optimal drilling and blasting parameters without the need to use resource-intensive finite-element calculations at each iteration. The second inequality of the constraint system strictly limited the seismic effect on the boundary rock mass, where K_s and α – the structural attenuation coefficients of seismic waves, R – the distance to the object, and K_{ppv} (θ, β) accounted for the spatial redistribution of seismic energy vectors depending on the direction of the shaped charge impact. The subsequent block of inequalities determined the limit boundaries of the spatial search for geometric parameters.

The solution of this complex multi-parameter problem was performed by the iterative algorithm of the Generalized Reduced Gradient (GRG). The choice of exactly this advanced method was justified by the significant nonlinearity of the fragmentation quality and seismic action constraints. The GRG procedure was specially adapted to maintain strict solution feasibility at each iteration. At the first stage, the general vector of variables was algorithmically divided into a vector of dependent basic variables (variable α) and a vector of independent non-basic variables $X_N = [\theta, \beta, W, L_p]^T$. The reduced gradient was calculated using the matrix equation $\nabla_R F = \nabla_N F(X) - \nabla_N g(X)[\nabla_B g(X)]^{-1}\nabla_B F(X)$, which required the calculation of the Jacobian matrix of first partial derivatives. To compensate for the linearisation error, a rigid correction procedure using the Newton-Raphson method was initiated after each optimisation step. The strictness of finding the global minimum was verified by checking the classical Karush-Kuhn-Tucker (KKT) conditions for the extended Lagrange function $L(X, \lambda) = F(X) + \sum \lambda_i \, g_i\,(X)$ (Fig. 2).

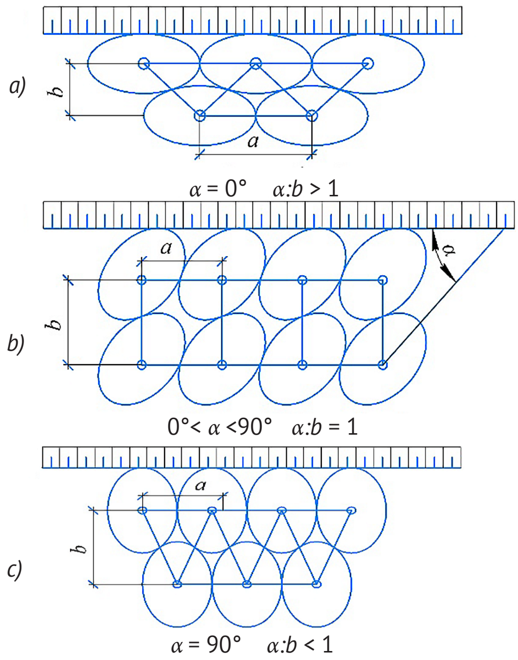

Figure 2. Orientation schemes of destruction ellipses from shaped charges for various topological configurations of the borehole pattern

Notes: *a)* $\alpha = 0^{\circ}$; *b)* $0^{\circ} < \alpha < 90^{\circ}$; *c)* $\alpha = 90$^∘

Source: developed by the authors

Since the numerical experiments generated data arrays with a certain level of stochasticity, a rigorous statistical apparatus was applied for their processing and integration into the macromodel. The assessment of the reliability of the differences obtained between the series of data indicators with different angles θ and β was conducted using one-way and multi-way analysis of variance (ANOVA) with the testing of null hypotheses using Fisher's F-test. The construction of surrogate models and the approximation of response surfaces (in particular, the dependencies of the borehole utilisation factor and the average fragment diameter on W, θ and β) were carried out by methods of multiple nonlinear regression using least squares algorithms (LSM). The quality and predictive ability of the obtained regression equations were evaluated using the adjusted coefficient of determination ($R^2_{adj} \geqslant 0.85$), and the statistical significance of individual model coefficients was confirmed by Student's t-test at a given confidence probability level $P = 0.95$. The detection and exclusion of anomalous outliers in the measurements were performed according to

Chauvenet's criterion, which ensured the robustness of the final empirical dependencies.

Based on the in-depth synthesis of the numerical modelling results and statistically confirmed experiments, a unified applied methodology for designing an optimised borehole pattern was formalised. This algorithm was conceptually based on the determination of the equivalent elliptical radius of the destruction zone. The optimal line of least resistance (W) was calculated as a nonlinear function of the linear charge density, the dynamic strength limit of the rock, and the angles of the spatial orientation of the jet (θ and β). Such a sharply anisotropic energy distribution necessitated the transition to rectangular or elongated rhombic spatial structures. The borehole spacing ratio ($m = a/W$) was calculated iteratively for each of the presented schemes, ensuring a precise tangential or secant collision of the expanded destruction ellipses exactly at the boundary of the elastic deformation zones. This radically minimised the overexpenditure of explosive energy on overcrushing and maximised the borehole utilisation factor due to the complete elimination of toe formation at the bench floor. All the presented model parameters, mathematical boundaries, and physical-mechanical characteristics were clearly documented, which ensured the scientific reproducibility of computer simulations under the conditions of similar iron ore deposits.

Results

Based on the array of data obtained during a series of experimental blasts in the fractured ferruginous quartzites of the Kryvyi Rih basin, the patterns of destruction zone formation depending on the spatial orientation of ESCs were analysed. Considering the high strength and pronounced structural anisotropy of the investigated rocks, the spatial control of explosion energy acted as a key factor in the optimisation of drilling and blasting parameters. The analysis of the explosive destruction parameters revealed a nonlinear dependence between the inclination angle of the shaped charge liner (α) relative to the longitudinal axis of the borehole and the geometric dimensions of the deformation zones. An increase in the angle α was accompanied by a shift in the maximum stress concentration, which led to a change in the equivalent radii of the intensive fragmentation zone (R_d) and the radial crack zone (R_c). The geomechanical mechanism of this phenomenon consisted in a change in the action vector of the detonation products: with the inclination of the shaped charge jet, a more efficient shearing of the structural blocks of the rock mass occurred, which minimised energy losses on plastic deformations directly around the borehole walls. As evidenced by the data presented in Figure 3, the dimensions of both zones demonstrated a statistically significant increase with an increase in the angle α from 0° to 45°.

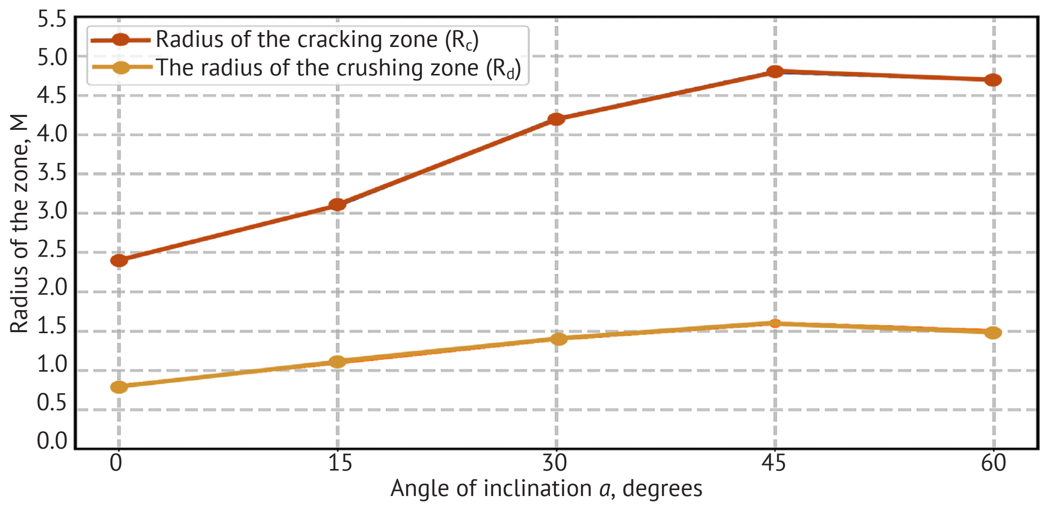

Figure 3. Dynamics of changes in the radii of the intensive fragmentation zones (R_d) and radial cracks R_c) depending on the inclination angle of the shaped charge liner

Source: developed by the authors

The results of the one-way analysis of variance (ANOVA) confirmed that the influence of the factor α on the size of the zone R_c was determining ($F = 42.6$; $p < 0.001$). At the same time, the post-hoc analysis using Tukey's test showed the absence of a statistically significant difference between the values of R_c and R_d in the range of angles of 45° and 60° ($p = 0.812$). This indicated the achievement of the limit of effective explosion energy redistribution in the rock mass. A further increase in the inclination angle (over 45°) led to the intensification of local rock overcrushing and the irrational expenditure of wave energy, which dissipated without the formation of new main cracks (Table 1).

Table 1. Statistical indicators of the sizes of destruction zones of ferruginous quartzites at various ESC orientations (n = 45)

ESC inclination angle (α),°	Radius of fragmentation zone (R_d), m	Radius of crack zone (R_c), m	Explosion energy utilisation factor (η), units
0 (baseline)	0.8 ± 0.1	2.4 ± 0.2	0.62 ± 0.04
15	1.1 ± 0.1	3.1 ± 0.2	0.68 ± 0.03
30	1.4 ± 0.2	4.2 ± 0.3	0.79 ± 0.05
45	1.6 ± 0.2	4.8 ± 0.3	0.86 ± 0.04
60	1.5 ± 0.2	4.7 ± 0.3	0.84 ± 0.05

Notes: data were presented in the format "mean value ± standard deviation"
Source: developed by the authors

As could be seen from the data in Table 1, the change in the spatial configuration of the charge directly influenced the explosive energy utilisation factor (η). In addition to the inclination angle, the influence of the azimuthal direction of the shaped charge jet (β) relative to the natural fracturing systems of the ore mass was quantitatively proven for the first time. Spearman's correlation analysis revealed a direct relationship (r_s = 0.84; p < 0.01) between the angle of the jet's encounter with the dominant crack system and the coefficient η. The maximum values η of were recorded provided that the ESCs were directed parallel to the strike of the rock mass or at an angle of up to 15° to the planes of weakness. In such a case, the "gas-dynamic wedge" effect was realised, where the detonation products penetrated into open natural cracks, expanding them and forming a continuous separation plane without additional energy losses on overcoming the resistance of the continuous medium. The established patterns of explosion energy redistribution served as a basis for adjusting the borehole pattern parameters. The directed increase in the radial crack zone (R_c) along the borehole row line allowed fundamentally changing the ratio between the line of least resistance (W) and the distance between the boreholes (α), designed in the rock mass. Due to the superimposition (superposition) of stress waves from adjacent charges oriented towards or parallel to each other, a single zone of guaranteed destruction was formed even with increased distances between the borehole axes. The data analysis (Table 2) demonstrated that the application of ESCs with an angle α in the range of 30-45° was accompanied by a proportional increase in the distance between boreholes a compared to traditional charges, whereas the value W of varied within the statistical error or demonstrated a tendency towards a slight decrease. The preservation or slight decrease W of was explained by the necessity of overcoming the rock resistance in the direction of the free bench surface to ensure high-quality separation and the formation of a rock pile with specified excavatability parameters.

Table 2. Design parameters of the borehole pattern for the Kryvyi Rih basin conditions depending on the ESC orientation

Charge type / Angle α,°	Line of least resistance (W), m	Distance between boreholes (a), m	Charge spacing ratio (m)	Specific drilling costs, m/m³
Traditional (columnar)	5.0 ± 0.2	5.0 ± 0.2	1.00 ± 0.05	0.0024 ± 0.002
ESC, α = 15°	4.9 ± 0.2	5.6 ± 0.3	1.14 ± 0.06	0.0021 ± 0.001
ESC, α = 30°	4.8 ± 0.2	6.5 ± 0.3	1.35 ± 0.08	0.0018 ± 0.001
ESC, α = 45°	4.6 ± 0.3	7.0 ± 0.4	1.52 ± 0.09	0.0016 ± 0.002
ESC, α = 60°	4.3 ± 0.3	7.2 ± 0.4	1.67 ± 0.10	0.0016 ± 0.002

Source: developed by the authors

The application of Student's t-test for independent samples confirmed that the increase in the charge spacing ratio when using ESCs (α = 45°) compared to the baseline variant was statistically significant (t = 6.8; p < 0.001). As a result of the pattern expansion (increase a to 7.0 ± 0.4 to m) a significant reduction in specific drilling costs by 33.3% (from 0.024 to 0.016 m/m³) was recorded. From an engineering perspective, this reduction not only reduced direct operational costs for rock mass preparation but also reduced the wear of drilling tools (roller cone bits), decreased the time equipment spent in the hazardous zone, and minimised the release of dust and gas clouds into the open-pit mine atmosphere. At the same time, the borehole utilisation factor (BUF) remained at the standard level 0.92 ± 0.03, which indicated the preservation of the full operability of the charges and the absence of negative phenomena in the form of "bootlegs". The economic feasibility of such an approach was justified by the fact that the additional costs for the shells themselves were statistically insignificant compared to the large-scale (by 33.3%) reduction in direct costs for drilling operations and the savings in tool life (Fig. 4).

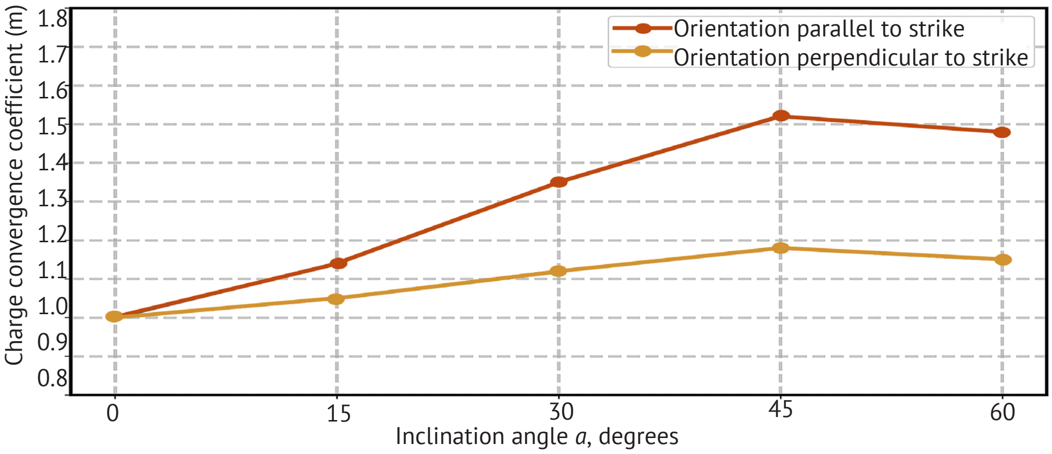

Figure 4. Empirical dependencies of the change in the charge spacing ratio (*m*) on the inclination angle (α) under the condition of jet orientation along (parallel) and across (perpendicular) the main fracture system of the rock mass

Source: developed by the authors

As reflected in Fig. 4, the maximum expansion of the borehole pattern was achieved exclusively under the condition of combined spatial orientation: an inclination angle of 45° with the simultaneous azimuthal direction of the shaped cavity parallel to the strike of the dominant crack system. In the case of directing the charge across the strike (perpendicularly), the increase in the coefficient *m* was levelled by the effect of energy shielding by open cracks. Due to the difference in acoustic impedance at the "rock – air or water-filled crack gap" boundary, a significant part of the compression wave energy was reflected in the form of a tensile wave, preventing the further propagation of the main crack in the specified direction. Under such conditions, the coefficient *m* reached an asymptotic maximum at the level of 1.18 ± 0.05. The obtained empirical dependencies $a = f(\alpha, \beta)$ and $W = f(\alpha)$ were a direct basis for the development of engineering nomograms. The process of practical utilisation of the results was envisaged as follows: relying on the data from the surveying and geological mapping of the structural blocks of the rock mass, the dominant azimuth of fracturing was determined. Furthermore, using nomograms, the spatial orientation of ESCs was established, which allowed maximising the destruction zone. At the final stage, the adjusted values of the distance between the boreholes and the line of least resistance were determined. Thus, designers under the conditions of the Kryvyi Rih basin open-pit mines received a substantiated toolkit for determining the optimal parameters of drilling and blasting operations, taking into account the structural and textural features of the local area.

Discussion

The physical understanding of the processes of targeted rock destruction using ESCs was significantly deepened by the obtained results, and conceptually new approaches to the design of drilling and blasting operations (DBO) were substantiated. A deep physical and mechanical explanation, associated with the focusing of liner elements and explosion products, was found for the identified increase in the radii of intensive fragmentation (R_d) and radial cracks (R_c) with an increase in the cavity inclination angle α to 45° with subsequent saturation of the effect. A study conducted by Z. Sun *et al.* (2024) was dedicated to the directed destruction of rocks using various liner materials and elongated slotted cavities. It was concluded by the authors that the application of such cavities allowed significantly reducing explosive energy losses on viscous destruction, which fully aligned with the identified 45% reduction of the plastic deformation zone radius in the hydrodynamic model. Furthermore, according to K.S. Ishchenko (2023), who investigated the blast parameters of charges with cavities of different cross-sectional shapes in the field of tensile stresses, it was established that the reduction of the peak pressure of detonation gases on the borehole walls in non-working directions prevented the transformation of rock into dust.

When comparing the obtained results regarding the mechanism of ESC action with the data dominating in modern literature, significant differences were observed. In particular, directed rock destruction using shaped charges with combined liners of various shapes was investigated by K. Liu *et al.* (2023), and it was pointed out that exactly the geometry of the shaped liner played a determining role in the formation of the shaped charge jet. In contrast to this, it was proven by the obtained results that for the conditions of mass blasts, not only the shape but also the density of the liner material was of critical importance. Since the use of expensive metals was economically unfeasible, the application of iron (pipe fragments) or aluminium allowed forming a high-speed "metal-gas-dynamic blade" that effectively cut through the rock.

The technological advantages of the proposed approach were emphasised by comparing the obtained results with modern methods of directed rock mass destruction. It was indicated by the results that the parallel orientation of the shaped cut to the crack system formed a sharply elongated elliptical destruction zone with a maximum energy utilisation factor ($\eta = 0.86$). During the research, it was established that the complex geometry of the open bench created exceptionally favourable conditions for the reflection of stress waves: the orientation of the shaped cavity strictly parallel to the line of least resistance maximised the synergetic effect of the interference of the direct compression wave and the oncoming unloading wave. Additionally, the mathematical and mechanical impact of the detonator's location on the bench blasting indicators was investigated by Q. Gao *et al*. (2020), and it was concluded that the optimisation of the initiation point was a critical factor in improving rock fragmentation quality due to the redistribution of stress wave directions. Also, a numerical study of an innovative shaped charge approach to rock destruction was conducted by Y. Yao *et al*. (2021), and a significant influence of microsecond delay intervals on the nature of crack formation was revealed, which confirmed the importance of the temporal and spatial positioning of charges.

The indisputable efficiency of the combined approach, where the solution of the mathematical programming problem ensured the transition from micro-models of destruction to open-pit macroparameters, was proven by an in-depth analysis of the obtained results. It was clearly demonstrated by the formulation of the nonlinear programming model with the objective function of reduced costs that the relationship between the direction of explosive energy and the pattern parameters could not be selected empirically without violating the system of technological constraints. It was mathematically proven by a detailed analysis of Lagrange multipliers that traditional technologies operated on the verge of acceptable fragmentation quality, whereas spatial energy control expanded this limit. Mathematical strictness in finding the parameters of the highest economic efficiency was provided by the use of gradient methods (Generalised Reduced Gradient – GRG) for problems of this class. In particular, according to M.N. Nawaz *et al*. (2022), the high efficiency and stability of the GRG method were proven in minimising costs under complex engineering and geological conditions. Also, the GRG method was applied for the approximation of dynamic coefficients in studies by H. Hasanudin *et al*. (2023), and its convergence was mathematically confirmed when searching for parameters in multifactorial models of a nonlinear nature.

The proven possibility of radical optimisation of the borehole pattern was the main result of such controlled formation of the destruction zone. The 18-22% increase in the pattern parameters obtained by the algorithm (в distance a increased to 7.0 ± 0.4 m at $W = 4.6 \pm 0.3$ m) fully confirmed the conclusions of international studies conducted by K. Bedri *et al*. (2023). Fragmentation during the blasting of fractured rock masses was analysed, and it was concluded that the spatial optimisation of drilling directions and pattern parameters allowed significantly reducing the total volume of drilling operations. However, as evidenced by the analysis of active constraints in the GRG algorithm, an extremely high sensitivity of the objective function to the charge installation angle was revealed: a deviation of more than 15 degrees from the optimal vector instantly activated the constraint on the ore fragment size, blocking the pattern expansion. This mathematical phenomenon was identical to the technological obstacles identified by J. Guo *et al*. (2024). The forecasting and optimisation of blasting parameters in open-pit mining operations using intelligent algorithms were investigated, and it was concluded that the failure to maintain charge positioning accuracy led to the instantaneous violation of technological constraints regarding the size of ore fragments. Shaped charge blasting technology for directed destruction was also studied by Q. Zhang *et al*. (2021), and it was found that this method provided high contouring accuracy and minimisation of explosive energy deviations, which confirmed the necessity of strict spatial control. Nevertheless, clear physical limitations were also revealed by the comparative analysis. The identified effect of rigid shielding when orienting the cavity across the cracks (spacing ratio $m \leqslant 1.18$) was consistent with classical results in the field of wave dynamics. Due to the sharp discrepancy in acoustic impedances at the "rock – empty crack" media boundary, the majority of the energy was reflected back into the rock mass, which made the artificial formation of an ellipse and pattern expansion under such conditions impossible.

When comparing the obtained results with the results of authors who investigated the optimisation of DBO in the Kryvyi Rih basin, a fundamental difference was observed. In particular, the experimental application of new materials and the variability of drilling and blasting parameters in a Kryvbas open-pit mine were studied by H. Yeremenko *et al*. (2022), and the focus was placed on the technological aspects of increasing blast efficiency. A methodology for the rapid determination of flyrock distance to ensure the safety of blasting operations was developed by Ye.O. Nesmashnyi *et al*. (2022). By comparing these works, it could be noted that none of the cited studies considered an integrated approach based on the synergy of mathematical programming, natural fracturing of the rock mass, and the shaped charge effect as a basis for the structural transformation of the pattern. In addition to the direct comparison of parameters, the 33.3% reduction in specific drilling costs without deterioration in fragmentation quality confirmed the conclusions published by O. Tverda *et al*. (2021). Resource-efficient and environmentally safe charge designs were proposed, and it was concluded that the implementation of such solutions proportionally reduced the technogenic load on the environment.

An in-depth analysis of scientific literature demonstrated that despite a significant number of publications dedicated to directed destruction and numerical optimisation methods, the majority of researchers analysed these issues in isolation. In particular, insufficient attention was paid to the mathematical modelling of conditions under which spatial control of explosive energy was directly integrated into borehole pattern parameters through nonlinear programming, taking into account the anisotropy of natural fracturing. Classical DBO design methods remained predominantly empirical, whereas existing nonlinear programming models did not account for the geodynamic influence of the shape and orientation of the shaped cavity on the elliptical destruction zone in hard ferruginous quartzites. Exactly these aspects of the topic, to which insufficient attention was paid by researchers in the analysed works, served as the motivation and direct impetus for conducting this study. Summarising, the comparison of the obtained results with research data proved that the integration of computational algorithms of nonlinear programming with the controlled spatial orientation of ESCs was a highly effective tool for DBO design. The empirical limitations of classical methodologies were overcome by the proposed combined approach, ensuring a mathematically rigorous and economically justified expansion of the borehole pattern.

Conclusions

As a result of the conducted research and computer modelling, the patterns of the influence of the spatial orientation of elongated shaped charges on the geometric parameters of the borehole pattern under the complex conditions of the Kryvyi Rih basin were established. It was proven that the development of the intensive fragmentation zones (R_d) and radial cracks (R_c) possessed a nonlinear dependence on the rotation angle of the shaped cavity (α) around the longitudinal axis of the borehole relative to the bench plane and the natural fracturing of the rock mass. Geomechanically, this was expressed in the formation of a destruction ellipse, where the change in the angle determined the orientation of its major axis, influencing the ratio between the distance in a row and the line of least resistance. The effect of structural "saturation" was confirmed by the analysis of variance (ANOVA): the rotation angle was optimal, at which a "gas-dynamic wedge" was formed, which most effectively opened the planes of weakness. A further increase in the angle (over 45°) did not provide a significant increase in the destruction zones, but only intensified local rock overcrushing and caused an irrational dissipation of wave energy.

The established patterns of energy redistribution substantiated the transition from square or triangular patterns to elongated rectangular or rhombic spatial structures, where the destruction zones of adjacent charges intersected at the boundary of elastic deformations, preventing the formation of intact rock pillars. Directing the shaped charge jet parallel to the strike of the main cracks (angle 45°) allowed increasing the distance between boreholes *a* to 7.0 ± 0.4 to m with an increase in the spacing ratio to 1.52 due to the superposition of oncoming stress waves. Conversely, the orientation of the charge across the strike caused acoustic energy shielding. Due to the difference in acoustic impedance at the "rock – crack" boundary, the compression wave was reflected in the form of a tensile wave back into the rock mass, which blocked the development of the destruction ellipse and limited the marginal spacing ratio at the level of 1.18. The prospects for further research consisted in the adaptation of optimisation algorithms for rocks with other physical and mechanical properties and types of anisotropy in the Kryvyi Rih basin. In particular, the behaviour of plastic rocks and rock masses with chaotic fracturing, where wave shielding was subject to other patterns, required investigation. A separate relevant direction was the investigation of the impact of the spatial orientation of charges under the conditions of multi-row short-delay blasting, where the interference of stress waves from the expanded borehole pattern would require the design of new initiation sequences and the adjustment of drilling and blasting parameters.

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Conflict of Interest

None.

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Вплив орієнтації подовжених кумулятивних зарядів на проектування оптимальної сітки свердловин для умов Криворізького басейну

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Анотація. Актуальність дослідження зумовлена необхідністю підвищення ефективності буровибухових робіт на залізорудних кар'єрах Криворізького басейну шляхом застосування подовжених кумулятивних зарядів, просторово адаптованих до структурних особливостей гірських порід задля оптимізації параметрів сітки свердловин. Метою роботи було встановлення закономірностей впливу просторової орієнтації подовжених кумулятивних зарядів на геометричні параметри сітки свердловин та розробка інженерних рекомендацій щодо її оптимального проектування в складних гірничо-геологічних умовах відкритого видобутку. Методи аналізу базувались на комплексному підході, що поєднує чисельне моделювання хвильової динаміки суцільних середовищ із використанням моделей поведінки матеріалів, математичне нелінійне програмування за алгоритмом узагальненого зведеного градієнта. Отримані результати доводять нелінійну залежність розмірів зон інтенсивного дроблення від кута повороту кумулятивної виїмки. Статистично підтверджено, що оптимальним є кут 45° за умови орієнтації струменя паралельно до простягання магістральних тріщин. Це дозволяє сформувати видовжену еліптичну зону руйнування та перейти від квадратних сіток до прямокутних просторових структур. Встановлено, що така конфігурація дозволяє збільшити відстань між свердловинами до 7 м і досягти коефіцієнта зближення зарядів на рівні 1,52. Водночас орієнтація заряду перпендикулярно до тріщин викликає ефект акустичного екранування енергії, що обмежує розширення сітки. Практична цінність досліджень полягає у розробці диференційованої методології просторового позиціонування вибухових зарядів у залізистих кварцитах. Впровадження запропонованих оптимізованих параметрів сітки свердловин забезпечує зниження питомих витрат на буріння на 33 % без погіршення якості дроблення. Це суттєво зменшує знос бурового інструменту, скорочує тривалість підготовчого циклу та пропорційно знижує екологічне навантаження на довкілля через зменшення обсягів пилогазових викидів

Ключові слова: кумулятивна виїмка; руйнування залізистих кварцитів; моделювання динаміки; зближення свердловин; буровибухові роботи