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EXPERIMENTAL SPECIFICATION OF THE NATURE OF ROCK MASS FRAGMENTATION BY BLASTING OF BOREHOLE CHARGES OF VARIABLE LENGTH

The object of this study is the process of rock mass destruction in open-pit mines during large-scale blasting operations using borehole charges of variable length. The deficiencies identified during the experimental audit include the discrepancy between the particle size distribution of the blasted rock mass and the design parameters. This mismatch is particularly evident under conditions of geogenic and anthropogenic disturbances, zones with variable bench heights, and contacts between different types of rock. One of the most problematic areas includes sections with developed fracture systems, which influence the propagation of blast waves and lead to zones of anomalous destruction and increased proportions of oversized rock fragments.

The inconsistency between the actual and calculated particle size distribution of the blasted rock mass in disturbed rock bodies complicates the design of blasting operations and the execution of technological processes in open-pit mining. This challenge becomes even more significant when mining activities are conducted in close proximity to urban development.

The research utilized experimental blasting methods, stepwise excavation with photographic documentation, and visual analysis of fragmentation zones, taking into account the length of charges and detonation delays. A qualitative outcome was achieved: the hypothesis regarding the regularities in the formation of volumetric zones in the rock mass was confirmed. Within these zones, the rock mass fragmented by the blast exhibits a relatively uniform particle size distribution. It was established that the key factors influencing the efficiency of explosive fragmentation in heterogeneous rock masses are the degree of natural fracturing and the detonation velocity (brisance) of the explosives. Observations from the layer-by-layer excavation of the fragmented rock partially confirmed the predicted effects of intentional variation in delay times between charges within groups of blast boreholes.

As a result, the blasting process becomes more technologically controllable, leading to improved granulometric composition of the rock mass and a reduction in the proportion of oversized material. Compared to traditional blasting schemes, the use of variable-length borehole charges allows for more effective adaptation to the complex structure of the rock mass and to conditions involving proximity to urban infrastructure, thereby providing technical and economic advantages in open-pit mining operations.

Keywords: *open-pit mine, anthropogenically disturbed rock mass, explosive fragmentation, adaptive large-scale blast design, fracture wave-guiding effect, particle size distribution.*

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1. Introduction

Experience with drilling and blasting (D&B) operations in complex mining and geological conditions often reveals blast performance indicators that differ significantly from theoretical predictions [1]. This discrepancy is particularly important when assessing the particle size distribution of rock mass prepared for excavation through blasting. The relevance stems not only from the fact that granulometric composition is a primary criterion for evaluating blast quality [1] – especially in terms of excavability – but also due to the significant impact that internal weakening of ore fragments has on subsequent beneficiation processes. This contradiction underlies a problem that has become increasingly pressing in recent years.

A review of contemporary publications on D&B technologies [2–4] confirms the existence of contradictory interpretations of various physical processes involved in productive blasting. In particular, different calculation methodologies often produce diverging results, which complicates practical engineering tasks in the design and implementation of geotechnological operations, including D&B [5, 6]. Given that the open-pit where this experiment was conducted is located in a rock mass heavily disturbed by previous mining activities, it is essential to consider the operational experience of similar deposits [7, 8]. Moreover, since the open-pit is located in the central part of the city and is surrounded by buildings, infrastructure, and roads, studies on the stability of tailings dams [9] and embankments [10] were also taken into account.

The unresolved aspects of the identified discrepancies point to the limitations of current approaches to analytical modeling of large-scale blasting processes. These limitations are primarily due to the insufficient integration of wave phenomena, particularly shock wave propagation in heterogeneous rock environments. A significant challenge in this regard is accounting for multiple reflections and refractions at interfaces between rocks of varying acoustic impedance. Additional complications arise from the mutual superposition of waves in fractured rock masses, which is often not adequately addressed in existing models. A partial theoretical explanation of rock fragmentation due to wave superposition is offered in studies [11, 12].

In [13], the authors investigated the impact of explosive materials and rock mass properties on blast-induced damage using numerical simulations validated with field data. Notably, the study addressed similar conditions and research objectives, as well as unresolved issues related to the influence of microstructures on shock wave behavior and forecasting methods. These insights motivated us to explore the applicability of the simulation logic in designing the experiment described in this paper.

Study [14] examined rock fragmentation characteristics during blasting using various coupling media, focusing on strain rate and loading. Given the presence of blast-sensitive infrastructure near the "Pivdennyi" open-pit, the findings support the potential transfer of these developments to Kryvbas conditions. However, a key challenge remains the difficulty of measuring strain rates in close proximity to boreholes, which necessitates further advancement of instrumentation techniques.

In [15], the authors visualized the evolution of impacts and crack propagation in fractured rock masses under blast loading. However, the developed methodology is only partially applicable to the present experiment, as it does not fully account for complex fracture networks typical of Kryvyi Rih deposits, nor does it adequately capture post-blast damage propagation for optimizing blast designs.

The study in [16] analyzed the energy efficiency of seismic waves in D&B operations and their influence on rock fragmentation. However, it lacked accurate models for predicting seismic responses across different rock types, indicating a need for improved seismic simulation capabilities.

In [17], the authors investigated blast-induced fracturing using decoupled charges in rock cylinders, focusing on the effect of charge confinement. The main unresolved issue remains the achievement of stable fragmentation in heterogeneous rock and under variable energy distribution.

Study [18] presented a numerical approach to tunnel blasting using specialized charges in hard rocks. Its main limitation lies in the model's inability to fully capture the complexity of crack initiation and development in layered or highly fractured rocks typical of the "Pivdennyi" open-pit. Nonetheless, it offers potential for designing minimally seismic blasting operations.

In [19], the authors explored excessive blast-induced damage during tunnel excavation in hard rock using both experimental and numerical methods. The unresolved issue remains how to reduce secondary damage while maintaining effective rock breakage within the design contour.

In [20], the importance of pressurized borehole drilling with decoupled charges was analyzed with a focus on optimizing explosive energy. Further research is needed to quantitatively evaluate the link between charge structure and blast efficiency under different geological conditions.

Study [21] experimentally assessed the attenuation law of shock waves in fractured rock masses during blasting, which closely aligns with the conditions and objectives of the experiment conducted at the "Pivdennyi" open-pit mine operated by LLC "Rudomain" (Kryvyi Rih, Dnipropetrovsk region, Ukraine). However, a major challenge remains in accurately predicting the influence of fracture spacing and material properties on wave propagation during large-scale blasts.

In [22], the authors examined fragmentation mechanisms in borehole blasting, refining the understanding of explosive-rock interactions. However, further research is required for the practical implementation of their methodology, particularly in modeling the impact of rock heterogeneity on fragmentation dynamics.

In [23], mechanisms of rock destruction during blasting were studied with emphasis on optimizing fragmentation to improve mining efficiency. The authors analyzed various empirical and theoretical fragmentation models and proposed a new approach considering fragment shape, size, and geometric rupture characteristics. However, the influence of natural fracturing, stratification, and other structural heterogeneities – factors shown by experiments to significantly affect fragmentation in real conditions – was not addressed.

The aim of this research is to clarify the mechanism of explosive rock mass destruction in complex geological settings using variable-length borehole explosive charges. This need arises from existing shortcomings in current analytical approaches, which tend to be overly one-dimensional and fail to fully account for the interrelated high-dynamic processes that occur within rock masses during blasting. An additional goal was to offer an original interpretation of observed blast outcomes, particularly in cases where new effects of explosive action were recorded.

The results of this research may be applied to ongoing mining operations to refine the parameters of drilling and blasting processes in disturbed rock masses, thereby improving the quality of blast-induced fragmentation.

2. Materials and Methods

The object of this research is the process of rock mass destruction under complex geological and mining conditions, implemented through large-scale blasting using borehole charges of variable length. The experimental investigation is complicated by the heterogeneous structure of the rock mass, varying bench heights, the presence of fracture zones, and long-standing anthropogenic disturbances due to the extended operational history of the mine. Special attention was devoted to analyzing the impact of these factors on fragmentation efficiency and the conformity of the resulting particle-size distribution of the blasted rock to predefined technological specifications.

The experiment was carried out upon the request of the iron ore raw materials producer LLC "Rudomain" (Kryvyi Rih, Dnipropetrovsk region, Ukraine). The "Pivdennyi" open-pit, which is part of the company's mining complex, commissioned LLC "Blastko Mining Service" (Zlatoustivka village, Dnipropetrovsk region, Ukraine) to conduct blasting operations on January 5, 2024, in accordance with Contract No. 2303/21 dated March 23, 2021. According to the agreement, the borehole diameter was set at 250 mm, and the drilling grid pattern was 6.0 × 6.0 m.

Block No. 1 (Bench Level –34/–46 m, survey axes 40–0):

- 51 boreholes with a planned depth of 13 m;
- 9 boreholes with a planned depth of 12 m;
- 8 boreholes with a planned depth of 10 m;
- 4 boreholes with a planned depth of 8 m;
- 18 boreholes with a planned depth of 6 m.

The blasting operations within the scope of the experiment were performed by LLC "Blastko Mining Service" pursuant to Order No. 3-OD dated January 3, 2024, concerning the execution of a mass blast. According to the blasting schedule for January 2024 at the "Pivdennyi" open-pit of LLC "Rudomain", a mass blast using borehole charges was scheduled for January 5, 2024, at 14:00, at Block No. 1 (Bench Level –34/–46 m), in accordance with Blast Passport No. 1.

The total projected amount of explosives for the blast was 24,075 kg, including a maximum of 350 kg per delay stage at Level –34/–46 m (Block No. 1). The total number of boreholes was 90. The designated safety zones were as follows: 350 m for personnel, 150 m for equipment, and 50 m for infrastructure.

A specific characteristic of the "Pivdennyi" open-pit (LLC "Rudomain") is its highly confined operating environment, surrounded by the "Pivnichnyi" open-pit, underground mining operations of PJSC "ArcelorMittal Kryvyi Rih", and multiple facilities of other enterprises and municipal infrastructure (Fig. 1). Therefore, in accordance with safety requirements for organizing and executing mass blasting operations – and to ensure safe working conditions for personnel of PJSC "ArcelorMittal Kryvyi Rih's" underground mine – prior coordination of the mass blast at the "Pivdennyi" open-pit with this company was undertaken.

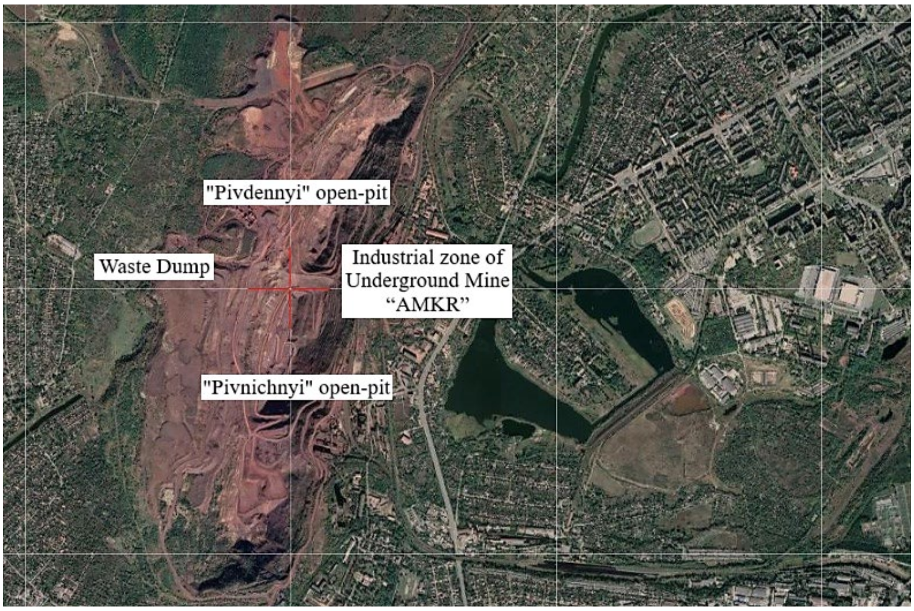


Fig. 1. "Pivdennyi" open-pit surrounded by facilities of other enterprises and urban infrastructure

An official readiness report dated January 1, 2024, was signed by the head of the open-pit operations department of LLC "Rudomain" and the head of the blasting division of LLC "Blastko-MS." The report confirmed that Block No. 1 at Level –34/–46 m, comprising 90 boreholes, was fully prepared for charging. The block was cleared of foreign objects and metal debris. Remarks during acceptance pertained to insufficient borehole depth in the following cases: No. 4 (–2); No. 5 (–2); No. 7 (–1); No. 8 (–0.5); No. 9 (–); No. (–0.5); No. 10 (–0.5); No. 11 (–1); No. 12 (–1.5); No. 15 (–2); No. 18 (–2); No. 32 (–2); No. 33 (–1); No. 35 (–1); No. 43 (–0.5); No. 44 (–0.5); No. 45 (–1.5); No. 46 (–3); No. 47 (–0.5); No. 61 (–1); No. 64 (–1); No. 69 (–2); No. 70 (–1); No. 71 (–1.5); No. 72 (–2); No. 82 (–1).

3. Results and Discussion

Despite the abundance of theoretical frameworks and their experimental validation, the effectiveness of drilling and blasting (D&B) operations in the open-pit development of ore deposits remains far from optimal. This persistent gap continues to drive improvements in contemporary models of explosive fragmentation of hard rock and the search for new technical solutions. Each new study aimed at refining calculation methodologies reveals a series of overlooked factors, due to which experimental results often deviate from theoretical predictions. These discrepancies present additional challenges in the implementation of geotechnological projects.

Analysis of the aforementioned scientific literature has made it possible to identify a potentially promising direction for uncovering the causes behind the shortcomings of current models namely – the mechanism of vector formation of critical loads and stress states in rock. Recent research shows that existing blasting models insufficiently account for the influence of acoustic anisotropy in the quasi-crystalline-like environment on the formation of the full stress tensor, which is a key factor in accurately predicting rock failure. As a result, the application of dynamic loading that reflects the actual mechanical properties of the rock remains approximate and is subject to systematic errors, which are typically compensated by various empirical correction factors. This highlights the necessity for further research and refinement of theoretical models to achieve high accuracy and reliability of D&B operations under complex geological conditions.

In a number of studies, these problems have been addressed with some success, yet the approaches to solving them remain fragmented. For instance, in [24], the authors separately investigated the evolution of the shock wave front as it reflects off free surfaces of the bench – both the slope and the bench top – and analyzed the superposition of this wave with that of a neighboring charge (Fig. 2). The visualization illustrates the sequential stages of shock wave formation and propagation over time, which is critical for understanding rock mass behavior under blast loading. Analysis of this process allowed us to refine our understanding of crack formation dynamics, which, in turn, contributed to improved prediction of rock mass behavior and optimization of blasting technology to minimize adverse impacts on bench stability and adjacent open-pit zones.

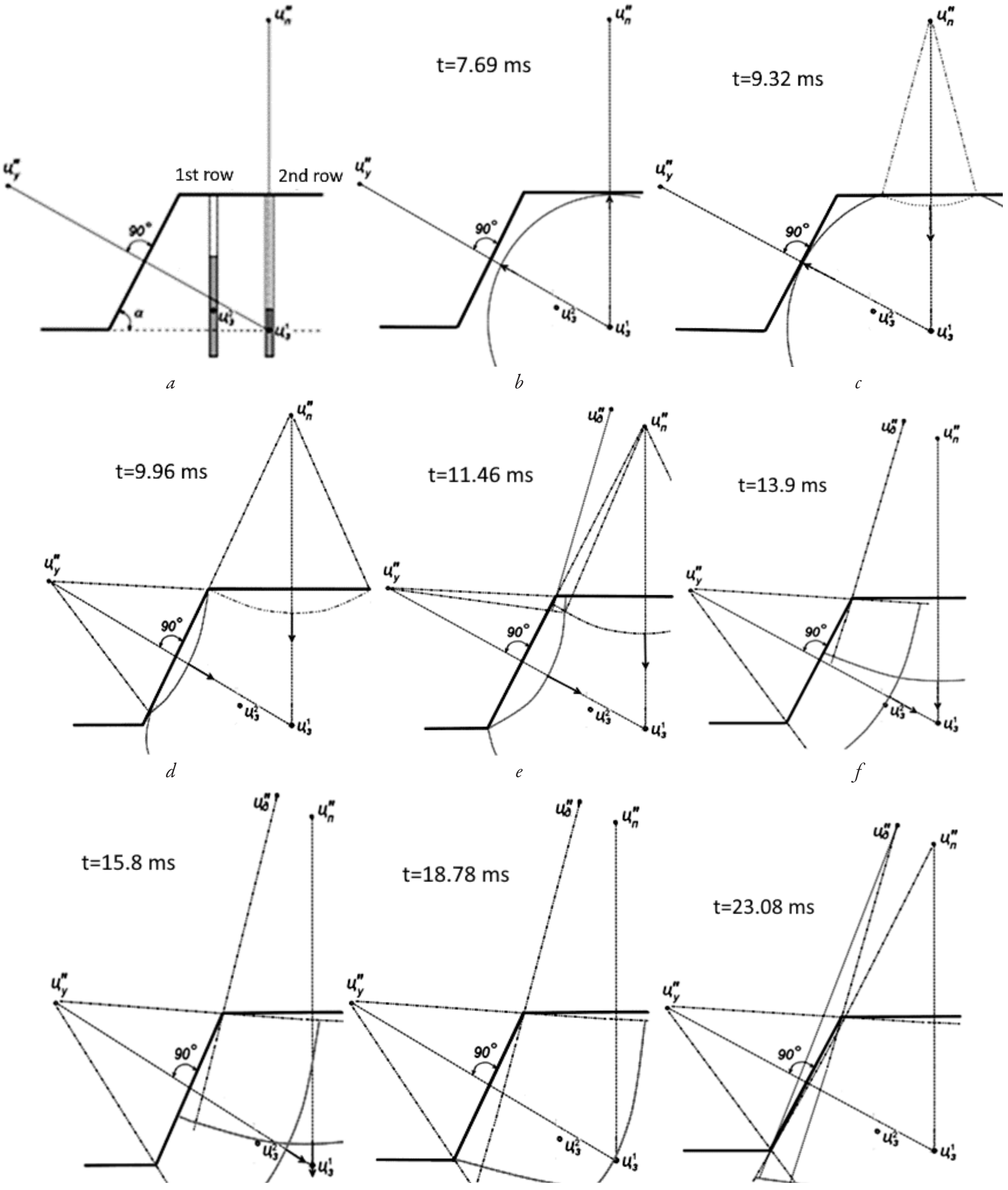
In turn, the author of [25] focused on the influence of rock mass anisotropy on waveguide formation in layered or blocky rock structures (Fig. 3). Differential energy saturation of the rock mass affects both the propagation of explosive waves and the development of fractures. As shown in Fig. 3, different charge arrangements impact the direction of crack formation and the distribution of stress within the rock. In our study, similar principles were employed in designing the blasting scheme, which enabled controlled influence over the destruction pattern and minimized the formation of oversized rock fragments. The approach proposed in [25], which accounts for the spatial directionality of explosive energy, allows for improved forecasting of the particle size distribution of the blasted rock mass and enhances the overall effectiveness of D&B operations in complex geological settings.

This segmentation of research indicates the need for integration of the obtained findings into a unified model that comprehensively reflects both shock wave reflection processes and the structural characteristics of the rock environment.

An experiment was designed to achieve more precise spatial and temporal recording of shock wave front propagation. The assessment of wave travel was performed using sensors installed within the blasting block. It is worth noting that the blast involved combined charges placed in boreholes of varying depths. Special attention was given to the subsequent analysis of the fragmented rock mass during stepwise excavation using an excavator. Operational performance data from the experimental blast are presented in Table 1.

Of particular importance is the fact that the experimental open-pit represents a unique example of anthropogenically disturbed rock across the entire open-pit field. This site marked the beginning of open-pit iron ore mining in the Kryvbas region, specifically using drilling and blasting technology, and has been continuously exploited for over 100 years. As such, it offers an irreplaceable basis for conducting advanced research on D&B operations. The geological complexity of the deposit is so atypical and diverse that it has been classified in the highest category of structural complexity. The rock mass, as a result of a century of explosive-induced vibrations, has become so disintegrated that it is formally recognized as anthropogenically altered.

Fig. 4, 5, respectively, show the borehole drilling design and the as-built wiring diagram of the blast initiation network, while Fig. 6 presents the zoning of the "Pivdennyi" open-pit (LLC "Rudomain") during the execution of the experimental mass blast.

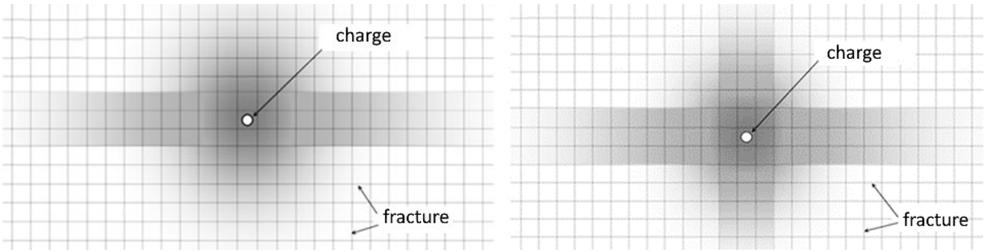


a *b* *c*

d *e* *f*

g *h* *i*

Fig. 2. Arrangement of borehole charges: *a* – in the bench, and evolution of the shock wave front upon reflection from free surfaces and superposition; *b*–*i* – interaction with the wave from another charge modeled as a point source from a linear charge



a *b*

Fig. 3. Effect of rock mass anisotropy on waveguide formation: *a* – in layered rocks; *b* – in blocky rocks, depending on the integrity of systematic fractures

Table 1

Operational Parameters of the Experimental Blast

Explosives used per block (HE)				Initiation system used per block (IS)	
Parameter	Unit	Planned	Actual	Name	Actual
Anemix P70/700	kg	126	126	DetEX MS 500/18	180
Anemix (total)	kg	25390	24075	Kapeksdet SD 0/100	1
Number of boreholes:	pcs.	90	90	DetEX SD 109/10	57
Total drilling length:	m	991.0	971.5	DetEX MS 67/10	50
Total blasted rock volume	m^3	35676	33696	ED-8-Zh-1m	2
Rock volume per running meter	m^3	36.00	36	–	–
Per 1 m^3 of rock	kg/m^3	0.7117	0.71	–	–

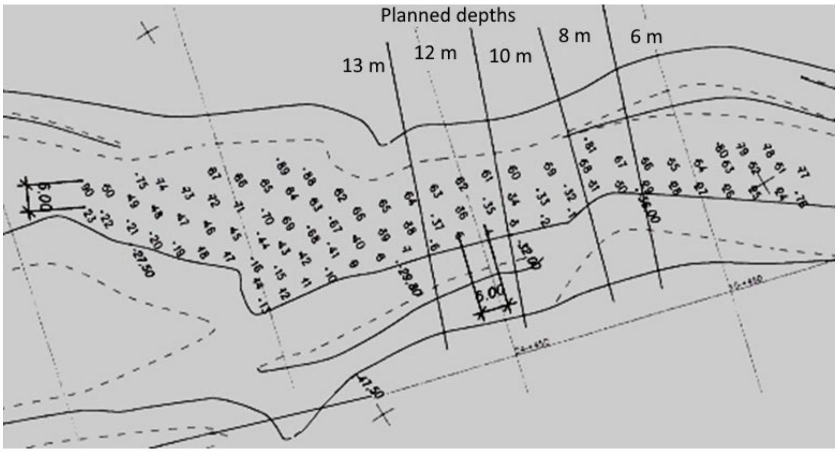


Fig. 4. Drilling layout for blast design

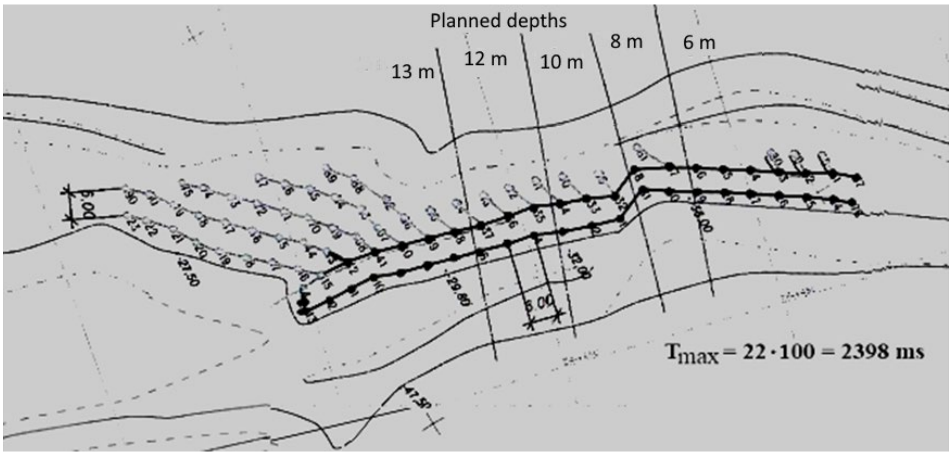


Fig. 5. As-built initiation system connection map

The experimental blasting conducted at the "Pivdennyi" open-pit enabled a more detailed investigation of rock destruction patterns under explosive loading. In particular, the relationship between the volume and degree of destruction of structural elements (natural blockiness) and their distribution in the blasted rock mass was studied in terms of proximity to the charge and original content in the undisturbed rock. Additionally, zones of maximum fragmentation were analyzed, and key factors influencing blasting efficiency were identified, such as interblock crack openness and explosive brisance.

The study demonstrated that blast parameters – specifically charge depth, placement, and detonation sequence – significantly affect fragmentation uniformity. Optimization of these parameters, taking into account the structural characteristics of the rock (fracturing and blockiness), enables a more even distribution of rock fragments, thereby enhancing the productivity of blasting operations and ensuring slope stability.

The optimization should be based on the minimization of the target function

$$\sum_i^n W_{D\&B} / \sum_j^m F_{proc.} < 1, \tag{1}$$

where $W_{D\&B}$ – additional costs resulting from changes in drilling and blasting (D&B) parameters; F_{proc} – reduction in costs related to raw material processing; $i...n$ – technical and technological measures aimed at reducing D&B expenses; $j...m$ – factors contributing to the reduction of processing costs.

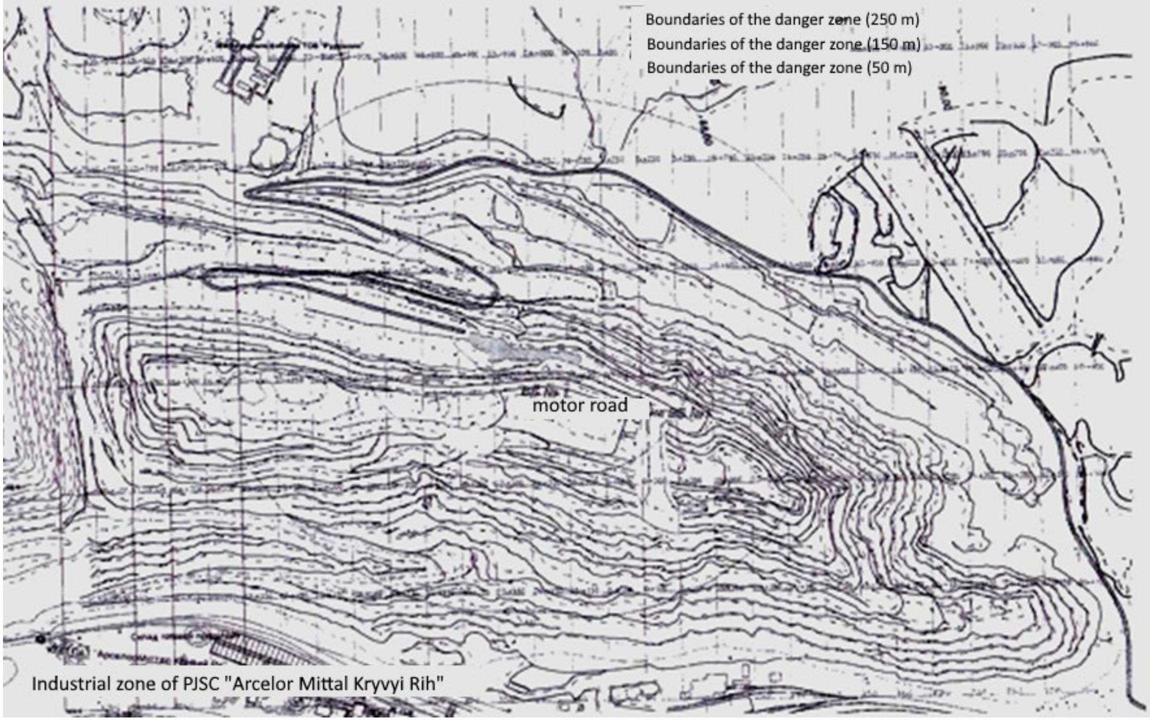


Fig. 6. Zoning of the "Pivdennyi" open-pit during the experimental blast

The final management decision in this regard requires a full-scale technological experiment and involves the introduction of empirical indicators.

However, an a priori – indicative assessment of the effectiveness of such technological adaptation is also possible. Within this framework, the formalization components for D&B include: the total borehole volume required to accommodate the full mass of explosives (HE); the increase in total borehole length due to a denser drilling grid using smaller diameters, in line with the required HE volume; changes in HE cost when its energetic and brisant characteristics are modified, taking into account specific consumption rates and overall volume, which in turn affects drilling volumes; the cost of additional or replacement initiation devices; temporal (time-based) evaluation of technological changes, both in D&B and subsequent beneficiation processes.

Such an assessment is purely indicative and must be subsequently verified through practical application.

Special attention was given to the analysis of the particle size distribution of the fragmented rock, selected from various quarries but similar in mineralogical composition and natural block structure. This allowed for further clarification of the patterns governing the formation of rock destruction zones (Table 2).

Table 2

Comparative Indicators of Rock Fragmentation by Granulometric Composition

Open-pit	*f* Rock Strength	Fraction Content (%) by Size Range (mm)					D_{avg}, mm
		0–200	201–400	401–800	801–1200	> 1200	
"Hannivskyi"	12–14	49.66	27.85	18.58	3.3	0.61	280
"Pivdennyi"	10–12	69.0	29.7	1.2	0.1	0.0	153.4

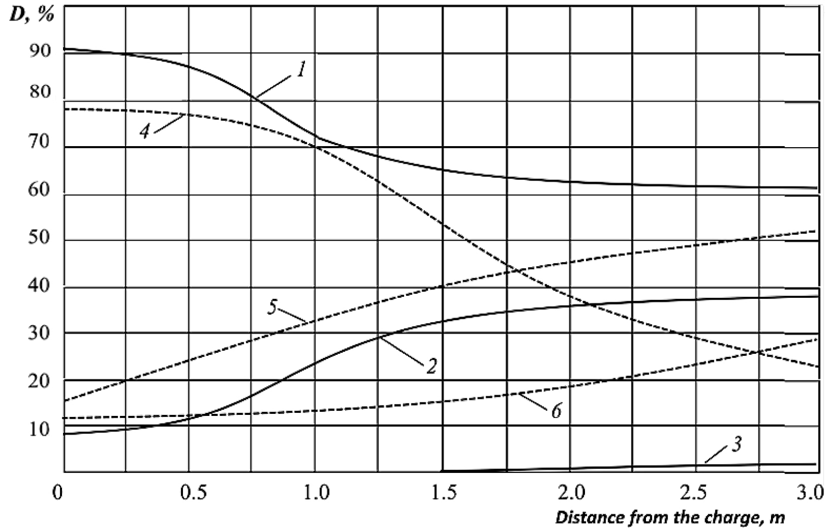


Fig. 7. Fragment distribution around charges in open-pit zones by size class (0–200, 201–400, > 401 mm): 1–3 – "Pivdennyi" open-pit (LLC "Rudomain"), 4–6 – "Hannivskyi" open-pit (Northern GZK)

It was found that uniform fragment distribution, without significant oversize or fines, is largely dependent on how the blast wave interacts with structural geological inhomogeneities. Observations during stepwise excavation (Fig. 7) showed that controlled variation of blasting parameters substantially improves process control, allowing fragmentation to be adjusted based on subsequent processing requirements.

The analysis also confirmed that structural variations significantly influence fragmentation outcomes, even under identical D&B parameters. This is attributed to varying crack propagation intensity based on fracture density and orientation in the rock mass. Some zones exhibit high fragmentation, while others yield oversized pieces requiring reprocessing.

These findings confirm the necessity of an adaptive approach to blast design, which takes into account local geological conditions and anthropogenic structural disturbances. This strategy not only improves fragmentation efficiency but also minimizes adverse effects such as inconsistent particle size, excessive oversize, and energy loss via seismic waves.

Use of optimized blasting parameters contributes to reducing environmental impacts and enhancing mining safety, key aspects of sustainable surface mining practices.

Unlike many prior studies [15–25] relying on simulations or controlled lab conditions, this research incorporated full-scale industrial experimentation in an anthropogenically disturbed mass. This enabled direct observation of waveguide formation, in-block fraction variability, and the role of spatial inhomogeneity under variable blasting scenarios.

In contrast to literature highlighting the difficulty of modeling geological anisotropy, our method experimentally identifies the effects of fracturing and blockiness on blasting performance. This led to the formulation of an adaptive D&B parameter optimization method that reflects real open-pit conditions and can be practically implemented in blast planning.

In conclusion, recent studies increasingly explore how explosives and rock mass properties influence fragmentation through both numerical and experimental methods. Yet challenges remain, including accurate prediction of microstructure effects on shock wave behavior, measuring deformation near boreholes, and adapting models to the specific geological conditions of the Kryvyi Rih Basin. These issues warrant further research and broader academic discussion.

The approaches proposed and results obtained in this study are based on site-specific data from the "Pivdennyi" open-pit (LLC "Rudomain"), where rock mass disruption is caused by both natural and anthropogenic factors. As such, the findings are directly applicable to similar conditions, particularly in deposits with high fracturing levels and long-term exposure to blast-induced stress.

Future experiments will focus on detailed studies of fragmentation and cracking zones under explosive loading. Particular attention will be paid to the spatial directionality of blast energy and its influence on rock breakage efficiency. A series of experiments is planned with varying charge masses, placements, and detonation sequences to identify optimal conditions for achieving desired fragmentation.

Moreover, modern modeling and monitoring tools will be utilized to deepen understanding of explosive-rock interactions and develop guidelines for improving D&B efficiency.

In summary, future research will aim to advance understanding of explosive rock destruction processes and develop scientifically grounded methods for optimizing blast parameters across diverse mining and geological environments.

4. Conclusions

The results of the experimental large-scale blast conducted at the "Pivdennyi" open-pit mine operated by LLC "Rudomain" confirmed the hypothesis regarding the main causes of the mismatch between the actual and calculated granulometric composition of the blasted rock mass. Layer-by-layer excavation of the blasted rock heap by the excavator revealed a significantly greater disproportion in the volumes of the hypothetical zones of maximum and optimal fragmentation.

For instance, at the comparable "Hannivskyi" open-pit of the Northern Mining and Processing Plant, the proportion of oversized rock fragments exceeded the calculated value by nearly 10%, while the content of over-fragmented material was limited to only 5.7%. In contrast, at the "Pivdennyi" open-pit of LLC "Rudomain", the proportion of over-fragmented rock mass exceeded the calculated yield by 7%, with an almost complete absence of coarse oversize. The primary reason for this phenomenon lies in both geogenic and anthropogenic structural disturbances, affecting not only the ore bodies but also the surrounding host rock mass. Particularly influential is the anthropogenic disturbance, which has progressively developed due to decades of periodic high-intensity vibrations from large-scale production blasts.

This situation is further complicated by the fact that the rock masses within the "Pivdennyi" open-pit field are subjected to blast impacts not only from internal operations but also from adjacent underground mining fields. Ore extraction in these underground workings is conducted using deep borehole charges with a diameter of 105 mm. The seismic effects of these blasts are significant both in terms of oscillation amplitude and the radius of influence. Such vibrations can cause pre-existing bedding, sub-latitudinal, and sub-meridional fracture systems to become through-going. As a result, the blocky fragments between them oscillate more freely, acting as inertial dampers to the blast waves intended to fracture the rock. These blocks not only weaken the blast waves but, together with the fractures, create waveguides that increase the unevenness of mass destruction and, consequently, the proportion of oversized rock fragments.

In addition to the above-mentioned factors, the use of short-delay blasting plays a significant role in this negative phenomenon. Under such conditions, vibro-rheological processes develop in the rock mass, causing relaxation-induced surface-layer damage of rock blocks. This contributes to the formation of off-grade, heterogeneously sized fine rock particles in the blasted mass.

The presented industrial experiments were mainly aimed at clarifying the mechanism of spontaneous particle-size polarization in blasted material, a highly undesirable outcome. This is because the greatest possible uniformity of the particle-size distribution is the primary quality criterion of drilling and blasting operations.

The research results contribute to a more refined understanding of rock mass destruction mechanisms under conditions of structural anisotropy and heterogeneity. The proposed interpretation of the formation of volumetric zones with varying degrees of fragmentation enables the enhancement of existing blast effect models by incorporating the wave-guiding properties of fractured media and the damping effect of blocky inclusions. This opens new possibilities for formalizing prediction criteria for the particle-size distribution of blasted rock mass based on rock mass characteristics and blasting regimes.

The findings from this experiment may be used to develop adaptive drilling and blasting schemes in open-pit mines located in complex geological and infrastructural conditions. Furthermore, they may serve to reduce adverse seismic effects on the environment and critical infrastructure facilities.

Conflict of interest

The authors declare that they have no conflicts of interest related to this research, including financial, personal, authorship, or any other form that could have influenced the study and its reported results.

Financing

This research was conducted without financial support.

Data availability

The manuscript does not contain associated data.

Use of artificial intelligence

The authors confirm that no artificial intelligence technologies were used in the creation of this work.

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