RGNZ/MGPB

Risk Management in the Construction of Metropolitan Running Tunnels Using Emulsion Explosives: Case Study

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
DOI: 10.17794/rgn.2026.4.8

Original scientific paper

Maksym Kononenko[1], Oleh Khomenko[2], Serhii Hapieiev[3], Roman Tereshchuk[3], Roman Dychkovskyi[2,4]*

[1] *Dnipro University of Technology, Department of transport systems and energy-mechanical complexes, 19 Yavornytskoho Ave., 49-005, Dnipro, Ukraine.*

[2] *Dnipro University of Technology, Department of Mining Engineering and Education, 19 Yavornytskoho Ave., 49-005, Dnipro, Ukraine.*

[3] *Dnipro University of Technology, Department of Construction, Geotechnics and Geomechanics, 19 Yavornytskoho Ave., 49-005, Dnipro, Ukraine.*

[4] *AGH University of Krakow, Faculty of Management, Al. Mickiewicza 30, 30-059 Krakow, Poland.*

Abstract

This study proposes a methodology for calculating the drilling-and-blasting parameters used in the construction of metropolitan running tunnels employing emulsion explosives within an integrated risk-management framework. Drilling-and-blasting operations in metropolitan tunnel construction require high precision in blast-hole design to ensure stable fragmentation and to minimize technical and operational risks. This study aims to develop a risk-oriented methodology for calculating drilling-and-blasting parameters for running tunnels based on the rational spatial arrangement of blast holes and controlled rock fragmentation. The proposed methodology is grounded in elasticity theory and quasi-static and wave-based hypotheses of rock failure under explosive loading. Blast holes are arranged in groups according to tunnel face areas using contour retreat principles. Straight cuts are designed based on the crushing zone radius, followed by calculations of the line of least resistance, explosive consumption, hole spacing, charge per hole, and total explosive expenditure. A power-law relationship is employed to define blast-hole geometry as a function of explosion pressure, hole diameter, uniaxial compressive strength, rock structure, jointing, and geostatic stress conditions. Numerical simulations confirmed the formation of stable inelastic deformation zones and uniform rock fragmentation, significantly reducing the occurrence of oversized blocks at the tunnel face. The study integrates analytical blast-design calculations with numerical stress–strain modelling within a unified risk-management framework for metropolitan tunnelling. Implementation of the proposed methodology improves blasting efficiency and safety, enables up to 14% savings in excavation resources, and reduces technical and operational risks associated with drilling-and-blasting works in urban underground construction.

Keywords:
drilling-and-blasting operations; emulsion explosives; stress–strain modelling; rock mass failure; tunnel excavation efficiency

1. Introduction

The rapid expansion of urban areas, accompanied by the construction of residential buildings, transport infrastructures, industrial facilities, and municipal structures, has intensified the competition for available land. In major metropolitan centers, the scarcity of free space has become a critical urban-planning challenge, limiting the establishment of new parks, pedestrian zones, and recreational areas. As cities continue to densify, the pressure on surface-level urban development increases, necessitating more efficient spatial planning strategies to ensure sustainable growth (**Haiko et al., 2023**).

To address these constraints, modern cities increasingly rely on the integrated use of both surface and subsurface spaces as a means of optimizing limited urban territory. Vertical urban zoning enables an effective redistribution of transport and pedestrian flows, separating high-speed and regular traffic as well as public and private mobility systems (**Pankratova et al., 2024a**). Within this framework, underground construction plays a vital role, providing alternative corridors for transport and utilities while simultaneously relieving the overloaded surface environment (**Pankratova et al., 2024a**). Such development not only enhances transport efficiency but also contributes to reducing visual clutter and improving the aesthetic quality of urban landscapes (**Pankratova et al., 2024a; Pankratova et al., 2024b; Cheberiachko et al., 2023; Pankratova et al., 2024c**). The rational development of underground space has therefore become a key direction in contemporary urban engineering, par-

* Corresponding author: Roman Dychkovskyi
e-mail address: dychkovskyi.r.o@nmu.one

Received: 13 December 2025. Accepted: 3 February 2026.
Available online: 21 July 2026

ticularly in high-density metropolitan areas (**Haiko et al., 2023; Cheberiachko et al., 2023; Pankratova et al., 2024c; Avanoğlu-Çetin & Öztürk, 2019**). Consequently, strategic planning and technological innovation in subsurface construction are increasingly essential for ensuring sustainable and resilient urban growth.

Among underground transport systems, metropolitan railways represent one of the most efficient solutions for reducing emissions, decreasing traffic congestion, and improving overall mobility in densely populated cities. By shifting a significant portion of passenger and freight traffic below ground, metro systems help alleviate surface-level transport pressure and contribute to more sustainable urban development (**Cheberiachko et al., 2023; Avanoğlu-Çetin & Öztürk, 2019; Alkhdour et al., 2023**). Their construction requires large-scale excavation of running tunnels, frequently conducted under complex geological and hydrogeological conditions that vary significantly between urban sites (**Radkevych et al., 2022**). These subsurface operations involve not only substantial engineering challenges but also strict requirements for environmental protection and structural stability (**Petrenko et al., 2023**). The use of drilling-and-blasting methods, while effective, introduces considerable technical, operational, and safety risks that must be carefully managed to prevent accidents and minimize adverse impacts (**Haiko et al., 2023; Pankratova et al., 2024c; Alkhdour et al., 2023; Petrenko et al., 2020**). Therefore, optimizing tunnel construction processes through advanced planning, risk assessment, and controlled blasting techniques is critical to the successful development of metropolitan railway infrastructure.

Given the growing demand for underground transport infrastructure and the increasing complexity of urban geological settings, there is a critical need for research aimed at improving the safety, predictability, and efficiency of blasting operations. The use of emulsion explosives in tunnel construction offers significant advantages but also requires advanced methodologies for blast-hole design, fragmentation control, and risk mitigation. Developing integrated risk-management approaches tailored to metropolitan running tunnels is therefore essential to ensure secure construction processes, minimize environmental and operational hazards, and enhance the overall sustainability of urban underground development.

Object of the Case Study. Currently, the city of Dnipro faces serious transport problems. Surface transport cannot cope with the passenger flow, leading to severe congestion in the city center. Residents of remote areas are forced to spend a significant amount of time travelling to the city center, not to mention the risks (**Cheberiachko et al., 2023; Zhang et al., 2024**) they face while using overcrowded minibuses (**Pankratova et al., 2024c**, **Lyashenko et al., 2018**). Analysis of the city's development and the functioning of urban passenger transport show that, in the short term, surface transport services will not be able to provide sufficient growth in passenger transportation, which confirms the need to develop an underground metro system. Therefore, considering the significant prospects for the development of Dnipro as one of the most important industrial, scientific, educational, cultural, financial, and business centers of Ukraine, further enhancing its international image and investment attractiveness, the completion of the metro construction is crucial for addressing the city's socio-economic development issues, improving transport infrastructure, increasing the quality of transport services, and achieving high operational efficiency and profitability. Another important factor highlighting the relevance of metro construction is the potential use of its underground infrastructure as a shelter, which has become particularly relevant due to Russian military aggression that has caused significant destruction to infrastructure in populated areas (**Cheberiachko et al., 2023; Myronova, 2016**).

The construction of a metro line is an especially dangerous, technically complex, and unique project with a Level I responsibility. Currently, the first stage of the Dnipro city metro (Dnipro Metro) includes six stations, a branch to the depot, and the depot itself, with a total length of 7.076 km. The extension of the first stage from the "Vokzalna" station to the "Muzeina" station is designed to connect the existing line with the central part of the city. The route alignment in plan and profile was determined based on the placement of stations in the main passenger-generating hubs, taking into account the existing urban development and geological and hydrogeological conditions. The extended line passes under Dmytra Yavornytskoho Avenue, where the stations "Teatralna," "Tsentralna," and "Muzeina" will be located (**Avanoğlu-Çetin & Öztürk, 2019; Krysin et al., 2004**). All stations are designed with island platforms long enough to accommodate five-car trains. Station vestibules are underground and connected to underpass crossings. Analysis of architectural and construction solutions for building vestibules (**Alkhdour et al., 2023; Kholodenko et al., 2014**), escalator passages (**Radkevych et al., 2022; Petrenko et al., 2023; Myronova, 2015**), and running tunnels (**Petrenko et al., 2020; Kononenko et al., 2023**) has shown that, to increase the efficiency of metro construction, technological solutions for intensifying tunnel excavation must be considered. One such solution is the use of rational blasting parameters (BPR), which improves work safety and leads to resource savings during construction (**Zhang et al., 2024; Kononenko et al., 2011**). Another improvement in blasting technology is not only enhancing the safety of explosive works (**Lyashenko et al., 2018**) but also reducing their environmental impact (**Myronova, 2016**) by replacing TNT-based explosives with domestically produced emulsion explosives (EEs) (**Krysin et al., 2004**), which are safe to transport and store (**Kholodenko et al., 2014**), cost-effective (**Kholodenko et al.,**

2015), and environmentally friendly (**Myronova, 2015; Kononenko et al., 2021**).

So, the aim of this study is to develop a new methodology for calculating blasting parameters for the excavation of metro running tunnels. This methodology takes into account key factors, such as the diameter of the blast holes, the pressure of the explosive products, and the compressive strength limits of the rock. In addition, it considers the structural composition of the rock, its fracturing, and the degree of compaction under in-situ stress, ensuring a more accurate and safe design of tunnel blasting operations.

2. Literature Review on Risk Factors and Management Approaches in the Construction of Metropolitan Running Tunnels Using Emulsion Explosives

The construction of metropolitan running tunnels represents one of the most technically demanding segments of underground infrastructure development. As cities expand and demand for efficient public transport increases, underground rail systems become essential elements of sustainable urban mobility (**Petrenko et al., 2023; Bashynska et al., 2024; Pivnyak, 2025**). However, tunnel construction in densely built urban areas is associated with severe geological, geotechnical, environmental, and technological challenges. The frequent necessity to work at significant depths, often in highly heterogeneous rock masses with variable water content, increases the complexity of ensuring structural stability and maintaining safe working conditions (**Kononenko et al., 2011; Vladyko et al., 2025**). In this context, blasting remains one of the primary excavation methods in hard-rock environments, requiring a sophisticated understanding of both the rock mass response and explosive performance.

The adoption of emulsion explosives has significantly reshaped blasting technology for underground tunnelling. Compared to traditional TNT-based or ANFO explosives, EE offer enhanced detonation stability, improved water resistance, controllable energy output, and higher operational safety (**Kholodenko et al., 2014; Kononenko et al., 2023; Listh, 1978**). Their properties make them especially advantageous in metro construction, where geological unpredictability and proximity to surface structures demand precise control of explosive effects. Despite these advantages, improper selection of blast parameters or inadequate design of drilling-and-blasting patterns can still lead to overbreak, excessive vibrations, rock mass loosening, equipment damage, and safety hazards (**Kononenko et al., 2023; Polyanska et al., 2024**). Therefore, comprehensive research into optimal EE application and associated risk-management strategies is timely and essential.

The use of explosive energy in confined underground environments introduces a spectrum of interrelated risks (**Pankratova et al., 2024b; Polyanska et al., 2025**). These include uncontrolled rock fracturing, excessive seismic vibrations, flyrock, gas contamination, unstable excavation walls, and unpredictable stress redistribution within the rock mass (**Pankratova et al., 2024b; Brown & Hudyma, 2016**). The magnitude and character of these risks depend not only on the physical and mechanical properties of the geological medium but also on drilling accuracy, explosive charging density, detonation velocity, and blast initiation timing. In metro construction, additional risks arise from the presence of nearby historical buildings, underground utilities, subway infrastructure, and sensitive architectural sites (**Pankratova et al., 2024b; Brown & Hudyma, 2016; Sala & Richert, 2025**). These factors elevate the consequences of blasting errors, making risk assessment and mitigation vital components of the construction process.

Although numerous national and international methodologies exist to guide drilling-and-blasting operations, many of them were developed using outdated explosive formulations and simplified assumptions about rock behaviour (**Kononenko et al., 2023; Kononenko et al., 2011; Gu & Cao, 2023**). A significant portion of these methodologies do not adequately account for the detonation characteristics of modern emulsion explosives, dynamic stress-wave interactions, or the complex mechanics of crack propagation in heterogeneous rock masses. Furthermore, available approaches often rely on empirical values with wide coefficient ranges, introducing uncertainty into the design of blast patterns (**Kononenko et al., 2023; Gu & Cao 2023; Pyzalski et al., 2025**). Thus, there is a clear scientific gap requiring updated analytical and computational tools that integrate modern explosive properties, advanced numerical modelling, and refined geological characterization.

The proposed methodology is clearly distinguished from existing analytical and empirical approaches by introducing several fundamentally new elements. These include an integrated risk-oriented framework that explicitly accounts for the formation of inelastic deformation zones and fragmentation predictability in metropolitan tunnelling. A physically justified blast-hole grouping strategy is implemented, linking tunnel face geometry with controlled contour retreat principles. In addition, a power-law relationship is proposed for determining the line of least resistance under urban tunnelling conditions using emulsion explosives, thereby enhancing the reliability and transferability of the design methodology.

The actuality of this research is driven by the rapid expansion of metropolitan transportation systems worldwide, accompanied by growing expectations for construction safety, environmental protection, and operational efficiency (**Pankratova et al., 2024b; Shcherba et al., 2025**). Authorities increasingly require evidence-based justification of blasting parameters to minimize ground vibrations, prevent structural damage, and ensure worker safety (**Gu & Cao, 2023; Ma et al., 2019**).

As projects grow in scale and societal importance, the economic consequences of blasting inefficiencies also intensify (**Serdaliyev & Iskakov, 2022**). Therefore, developing scientifically grounded, validated methodologies for evaluating risk factors and optimizing management strategies using emulsion explosives directly contributes to improving construction quality, reducing costs, and enhancing safety across the industry.

The current drilling-and-blasting design methods for metropolitan running tunnels are largely based on empirical rules, simplified deterministic formulas, or adaptations of mining-oriented practices that do not fully account for the specific constraints of urban tunnelling. The existing approaches typically treat blast-hole spacing, charge distribution, and explosive consumption as independent parameters, with limited consideration of their coupled influence on rock mass response, fragmentation uniformity, and operational risk. Moreover, most methodologies do not explicitly integrate risk-management principles, such as the control of oversized block formation, predictability of inelastic deformation zones, and variability in rock mass structure under geostatic stress. The use of emulsion explosives in metropolitan conditions further accentuates these limitations, as their energy release characteristics are often not adequately reflected in conventional blast design models.

The scientific novelty of this study lies in the development of an integrated, risk-oriented methodology that unifies analytical blast-parameter calculation, physically justified blast-hole grouping, and numerical stress–strain modelling within a single design framework. Unlike existing methods, the proposed approach establishes a power-law relationship between the line of least resistance and key geological, mechanical, and explosive parameters, enabling rational and predictable blast-hole layout design for tunnel faces. The methodology explicitly targets risk reduction by ensuring the formation of stable inelastic deformation zones and uniform fragmentation, thereby minimizing oversized blocks. This advances current knowledge by shifting drilling-and-blasting design from empirical tuning toward a physically grounded, predictive, and resource-efficient framework tailored to metropolitan tunnel construction using emulsion explosives.

This research provides an integrated understanding of risk factors associated with drilling-and-blasting operations in metro tunnel construction and outlines best-practice management approaches tailored to modern EE technologies. By combining field observations, analytical methods, and numerical modelling, it establishes a robust foundation for calculating rational blasting parameters and predicting rock mass behaviour. The outcomes may be used to refine construction guidelines, support decision-making for designers and engineers, and strengthen regulatory frameworks. Moreover, the findings help bridge the gap between traditional empirical methods and contemporary high-precision engineering practices, thereby contributing to the future development of safer, more efficient underground construction technologies.

3. Research Methodology, Methods & Materials

The choice of the technological scheme and the method of rock excavation during the construction of running tunnels is influenced by the engineering-geological conditions of the project area, the water saturation of the intersected rocks, rock pressure, and other factors (**Morelli, 2015**). Given the engineering-geological conditions of tunnel construction, the tunnels are located at a depth of 68 m in hard rock (granites) with a compressive strength of 49–123 MPa. Therefore, their construction will be carried out using a closed (underground) method with drilling-and-blasting operations (DBO). For the construction of the running tunnels from Shaft No. 16-bis to the "Muzeina" station, a full-face excavation scheme has been adopted (**Radkevych et al., 2022**). This technological scheme is applied for tunnelling in stable rocks with compressive strength $\sigma c \geq 40$ MPa and in workings not exceeding 10 m in height and 20 m in width. These geometric limitations are linked to the capability of drilling and auxiliary equipment, as well as to the risk associated with opening an unsupported span of considerable height in a single cycle.

It is well known that DBO is a set of work processes associated with the detachment of rock from the massif through the action of explosive energy. The term "DBO" emphasizes the inseparable and interdependent nature of the processes of drilling, charging, and blasting (**Kononenko et al., 2023; Gu & Cao 2023; Carlos et al., 2017**). Depending on how rationally the parameters of DBO are determined, they may significantly affect the technical and economic indicators of underground excavation. Currently, numerous methodologies exist for calculating DBO parameters in underground mine workings (**Kononenko et al., 2023; Mishra, 2012**). These methodologies vary in the complexity of their algorithms and often yield substantially different results. Therefore, several existing methodologies proposed by leading researchers from different countries are considered herein.

The first class of methodologies focuses on determining the specific explosive consumption, which is defined based on practical data, empirical formulas, or tabulated reference information (**Gu & Cao, 2023; Fedoreiko et al., 2025**). Based on the specific explosive consumption, the number of blast holes is calculated, followed by the remaining DBO parameters (**Bozic & Strelec, 2020**). A significant drawback of this approach is that the coefficients used in calculations cover a very wide range of values, and their selection depends largely on the designer's qualification (**Gu & Cao, 2023; Bozic & Strelec, 2020**). As a result, the DBO parameters are often defined using average values, which negatively af-

fect blasting efficiency and ultimately require additional trial blasts to refine rational DBO parameters (**Kononenko et al., 2023; Gheorghiosu & Becuţ, 2024**). The authors of these methodologies include Protodiakonov M.M., Bogomolov V.I., Pokrovskyi M.M., Mindeli E.O., Sukhanov A.F., Ibraev Sh.I., Taranov P.Ya., Langefors U., Borisova S.S., Roginskyi V.M., Bokii B.I., Baron L.I., and others. Analysis of the most common methodologies that rely on preliminary determination of specific explosive consumption shows that rock strength and cross-sectional area of the excavation are the key factors in all these approaches (**Kononenko et al., 2011; Fedoreiko et al., 2019**). Less frequently, the formulas include explosive performance, charging density, and blast-hole depth. The formulas were developed during the 1920s–1960s and were later refined by subsequent researchers, while some remain in their original form. Their major limitation is that they were developed for TNT-based explosives and do not account for the detonation characteristics of modern emulsion explosives (EE) (**Kononenko et al., 2021**).

Methodologies belonging to the second class differ fundamentally. These methods involve determining the zones of crushing and fracturing around a blast hole, depending on the physical-mechanical properties of the rock mass and the detonation characteristics of the explosive. Based on these zones, the minimum burden between groups of blast holes and the spacing within rows are calculated, after which the holes are arranged in the tunnel face. Andriievskyi O.P. (**Andrievskii, 1993**) proposed a methodology for calculating and designing the DBO plan for underground mine workings, which includes determining the radii of the crushing and fracture zones, with the latter used to define the minimum burden. The blast holes are arranged according to a calculated grid. Perimeter holes are placed uniformly along the contour at a spacing not exceeding the radius of the fracture zone, and their spacing is calculated separately. Building upon Andriievskyi's method, Vokhmin S.A., Kurchin H.S., and Kirsanov O.K. proposed an improved version through the introduction of an empirical formula for determining the detonation velocity of ammonium-nitrate-based explosives as a function of charge diameter and charging density. They also developed a graphical-analytical procedure for designing DBO parameters.

Therefore, based on the combined action of quasi-static and shock-wave mechanisms of rock destruction (**Kosenko et al., 2025**), and integrating both previously described methodological approaches, it is necessary to develop a new methodology for determining DBO parameters for the construction of metro running tunnels that accounts for both the physical-mechanical properties of the rock mass and the detonation characteristics of modern explosives.

The development of a methodology for determining DBO parameters for metro running tunnels included the following stages:

- design and sequential calculation of cut holes based on the radius of the crushing zone;
- development of a methodology for determining DBO parameters based on the principle of arranging groups of blast holes according to the areas they occupy in the tunnel face and their placement along breakage contours;
- verification of the calculated parameters of DBO with EE under real-world conditions using numerical modelling of the stress–strain state of the rock mass in the tunnel face under explosive loading.

To develop the methodology for DBO parameter determination during metro tunnel construction, the generally known laws of elasticity theory and the main principles of the quasi-static–wave hypothesis of solid-medium destruction by explosion were applied. Numerical modelling of inelastic deformation zones caused by changes in the stress–strain state of the rock mass under explosive action was performed using the finite element method in the licensed engineering analysis software SolidWorks Simulation.

When constructing running tunnels underground using blasting with emulsion explosives (BPE), the most common cross-sectional shapes are oval or circular. Therefore, the methodology for calculating BPE parameters in the construction of running tunnels will be developed for these two excavation shapes.

The procedure for calculating BPE parameters according to the new methodology consists of the following main stages. The first stage includes the calculation and design of the initial cut (**Kononenko et al., 2023**), and the second stage involves the direct calculation of the number of boreholes, their placement in the excavation face, and the total explosive consumption per face (**Khomenko et al., 2019**).

According to the research presented in **Kononenko et al. (2023b)**, the spacing between boreholes in the initial cut equals the radius of the crushing zone and is determined by the formula:

$$R_{zm} = 0.5 \cdot d \cdot \sqrt{1 + \frac{\rho \cdot D^2 \cdot K_{dz}}{2 \cdot \sigma_{st} \cdot K_{sp} \cdot K_s \cdot K_u}}, \text{ m}; \quad (1)$$

where d – borehole diameter, m; ρ – density of explosives or emulsion explosives (**Kononenko et al., 2021**), kg/m^3; D – detonation velocity of explosives, m/s; σ_{st} – compressive strength of rocks, Pa; K_{dz} – coefficient accounting for the change in pressure of explosive gases on the walls of the charge cavity depending on the charge diameter (**Kononenko et al., 2023b**); K_{sp} – rock structure coefficient, depending on rock mass properties (**Kononenko et al., 2023b**): for viscous, elastic, and porous rocks K_{sp} = 2.0; for dislocated rocks with variable bedding and fine fracturing K_{sp} = 1.4; for schistose rocks with variable strength and bedding perpendicular to the charge cavity K_{sp} = 1.3; for massive brittle rocks K_{sp} = 1.1; for monolithic rocks K_{sp} = 1.0; for fine-porous, loose

rocks K_{sp} = 0.8; K_s – coefficient of structural weakening of the rock mass, determined using one of the formulas in (**Kosenko et al., 2025**); K_u – empirical coefficient of rock compaction under mining pressure (**Kosenko et al., 2025**).

The minimum area of the initial cut is determined empirically as:

$$S_{vr} = 0.45 \cdot (l_{sh} \cdot \eta)^{0.91}, \text{ m}^2, \quad (2)$$

where l_{sh} – length of the borehole set, m; η – borehole utilization coefficient, 0.8–0.95.

The minimum number of boreholes in the cut, without accounting for compensatory (empty) holes:

$$N_{vr} = \frac{S_{vr}}{\pi \cdot R_{zm}^2}, \text{ pcs.} \quad (3)$$

According to the second stage, the following calculations are performed: borehole spacing, areas of borehole groups, number of boreholes, spacing between them, charge per borehole, specific and total explosive consumption for the tunnel face (**Kononenko et al., 2024**). The determination of explosive performance based on the degree of detonation velocity realization is carried out according to the methodology presented in **Kononenko et al. (2023c)**. The calculated specific explosive consumption is determined by the most universal formula of Prof. M.M. Pokrovskyi (**Kononenko et al., 2024**):

$$q = 0.01 \cdot \sigma_{st} \cdot K_{sp} \cdot k_{zat} \cdot e, \text{ kg/m}^3, \quad (4)$$

where σ_{st} – compressive strength of rocks, MPa; k_{zat} – rock confinement coefficient, ranging 1.2–1.5; e – relative performance coefficient of explosives, calculated according to **Kononenko et al. (2023c)**.

The volume of blasted rock in the mass is:

$$V = S_{pr} \cdot l_{sh}, \text{ m}^3, \quad (5)$$

where S_{pr} – tunnel area at the face:

$$S_{pr} = 0.25 \cdot \pi \cdot \text{B}_{pr} \cdot \text{H}_{pr}, \text{ m}^2, \quad (6)$$

with B_{pr} – tunnel width, m; H_{pr} – tunnel height, m.

The calculated explosive quantity per face:

$$Q = q \cdot V, \text{ kg}. \quad (7)$$

Considering the operating conditions of borehole charges, their placement relative to the open surface, and the need to crush the rock mass to pieces < 0.2 m, the calculation of borehole spacing is recommended based on the radius of the intensive crushing zone (**Kononenko et al., 2023b**).

Calculated borehole spacing:

$$W = R_{zm} \cdot \left(1 + \frac{\rho \cdot D^2 \cdot d \cdot K_{dz}}{8 \cdot R_{zm} \cdot \sigma_{st} \cdot K_{sp} \cdot K_s \cdot K_u}\right)^{0.5}, \text{ m}. \quad (8)$$

Contour borehole area:

$$S_k = S_{pr} - \pi \cdot \frac{\text{B}_{pr} - 2 \cdot (\Delta_o + W)}{2} \cdot \frac{\text{H}_{pr} - 2 \cdot (\Delta_o + W)}{2}, \text{ m}^2, \quad (9)$$

where Δ_o – distance from the excavation contour to the line of contour boreholes, equal to the radius of the crushing zone R_{zm}, typically 0.15–0.25 m based on practical experience.

Face area for production boreholes:

$$S_{vid} = S_{pr} - (S_{vr} + S_k), \text{ m}^2. \quad (10)$$

where S_{vr} – accepted cut area, m^2.

Number of production boreholes:

$$N_{r.v} = \frac{1.27 \cdot q \cdot S_{vid}}{\rho \cdot d_z^2 \cdot k_z}, \text{ pcs.}, \quad (11)$$

where k_z – borehole filling coefficient, 0.30–0.85, or calculated empirically (**Kononenko et al., 2023a**):

$$k_z = 0.225 \cdot \sigma_{st}^{0.25}, \quad (12)$$

where σ_{st} – compressive strength of rocks, MPa.

Area per production borehole:

$$S_{v.sh} = \frac{S_{vid}}{N_{r.v}}, \text{ m}^2. \quad (13)$$

Adjusted calculated borehole spacing:

$$W_{sr.v} = \sqrt{S_{v.sh}}, \text{ m}. \quad (14)$$

Distance between production boreholes in a row:

$$a_{r.v} = m \cdot W_{sr.v}, \text{ m}, \quad (15)$$

where m – charge convergence coefficient for production boreholes, 1.0–1.3.

Number of rows of production boreholes:

– across tunnel width:

$$n_{h.r.v} = \frac{0.5 \cdot B_{pr} - \Delta_o - 0.5 \cdot b_{vr}}{W_{sr.v}} - 1, \text{ pcs.}; \quad (16)$$

– along tunnel height:

$$n_{v.r.v} = \frac{0.5 \cdot H_{pr} - \Delta_o - 0.5 \cdot h_{vr}}{W_{sr.v}} - 1, \text{ pcs.}; \quad (17)$$

where b_{vr} and h_{vr} – width and height of the cut, m.

Actual distance between rows of production boreholes:

– across width:

$$W_{h.f} = \frac{0.5 \cdot B_{pr} - \Delta_o - 0.5 \cdot b_{vr}}{n_{h.r.v} + 1}, \text{ m}; \quad (18)$$

– along height:

$$W_{v.f} = \frac{0.5 \cdot H_{pr} - \Delta_o - 0.5 \cdot h_{vr}}{n_{v.r.v} + 1}, \text{ m}. \quad (19)$$

Optimal contour rows of production boreholes follow the tunnel cross-section shape.

Number of production boreholes in the i^{th} contour:

$$N_{v(i)} = \frac{2 \cdot \pi \cdot \sqrt{0.125 \cdot (b_i^2 + h_i^2)}}{a_{r.v}}, \text{ pcs.}, \quad (20)$$

where b_i and h_i – width and height of the i^{th} contour, m.

Actual spacing between boreholes in the i^{th} contour:

$$a_{f.v(i)} = \frac{2 \cdot \pi \cdot \sqrt{0.125 \cdot (b_i^2 + h_i^2)}}{N_{v(i)}}, \text{ m.} \quad (21)$$

Total number of production boreholes:

$$N_{vid} = \sum_{i=1}^{n} N_{v(i)}, \text{ pcs.} \quad (22)$$

Calculated distance between contour boreholes:

$$a_{r.k} = m \cdot W_{sr.v}, \text{ m}, \quad (23)$$

where m – charge convergence coefficient for contour boreholes, 0.75–0.95.

Number of contour boreholes:

$$N_k = \frac{2 \cdot \pi \cdot \sqrt{0.125 \cdot \left((B_{pr} - 2 \cdot \Delta_o)^2 + (H_{pr} - 2 \cdot \Delta_o)^2\right)}}{a_{r.k}}, \text{ pcs.} \quad (24)$$

Actual distance between contour boreholes:

$$a_{f.k} = \frac{2 \cdot \pi \cdot \sqrt{0.125 \cdot \left((B_{pr} - 2 \cdot \Delta_o)^2 + (H_{pr} - 2 \cdot \Delta_o)^2\right)}}{N_k}, \text{ m.} \quad (25)$$

Total number of boreholes in the tunnel face to be charged:

$$N = N_{vr} + N_{vid} + N_k, \text{ pcs.}, \quad (26)$$

where N_{vr} – number of charged cut boreholes, pcs.

Average charge per borehole:

$$Q_{sh} = \frac{Q}{N}, \text{ kg.} \quad (27)$$

Charge in a borehole according to its purpose:

$$Q_z = K_n \cdot Q_{sh}, \text{ kg}, \quad (28)$$

where K_n – coefficient accounting for increase or decrease of charge depending on borehole type: for cut borehole K_n = 1.1–1.2, for production borehole – K_n = 1.0, for contour borehole on sides and roof K_n = 0.9–1.0, for contour borehole on floor K_n = 1.0–1.2.

Actual explosive consumption per face:

$$Q_f = N_{vr} \cdot Q_{vr} + N_{vid} \cdot Q_{vid} + \\ + N_{bp.k} \cdot Q_{bp.k} + N_{p.k} \cdot Q_{p.k}, \text{ kg}, \quad (29)$$

where Q_{vr} – charge in cut borehole, kg; Q_{vid} – charge in production borehole, kg; $Q_{bp.k}$ – charge in contour boreholes at sides and roof, kg; $Q_{p.k}$ – charge in floor contour boreholes, kg.

Actual specific explosive consumption:

$$q_f = \frac{Q_f}{V_f} = \frac{Q_f}{S_{pr} \cdot l_{sh} \cdot \eta}, \text{ kg/m}^3. \quad (30)$$

Length of boreholes filled with blasted material:

$$L_{zab} = l_{zab.vr} \cdot N_{vr} + l_{zab.vid} \cdot N_{vid} + \\ + l_{zab.bp.k} \cdot N_{bp.k} + l_{zab.p.k} \cdot N_{p.k}, \text{ m}, \quad (31)$$

where $l_{zab.vr}$, $l_{zab.vid}$, $l_{zab.bp.k}$ and $l_{zab.p.k}$ – lengths of cut, production, side and roof contour, and floor contour boreholes, m.

Mass of blasted material:

$$M = 0.25 \cdot \pi \cdot d^2 \cdot L_{zab} \cdot \rho_{zab}, \text{ kg}, \quad (32)$$

where ρ_{zab} – density of blasted material, kg/m^3.

The presented methodology and mathematical framework provide a systematic approach for calculating blasting parameters in the construction of underground metro tunnels. It allows for accurate determination of borehole placement, charge distribution, and explosive consumption under practical field conditions. The approach is adaptable to both oval and circular tunnel cross-sections, enhancing operational efficiency and safety. Overall, this method offers a reliable tool for optimizing excavation processes in urban underground construction.

4. Results of Management Solutions for the Construction of Metro Running Tunnels Using Emulsion Explosives: Shaft No. 16-bis to "Muzeina" Station, Dnipro city

As an example, let us consider the calculation of blasting parameters for the construction of the running tunnel from Shaft No. 16-bis to the "Muzeina" station of the Dnipro city metro (Dnipro Metro). The calculation is based on the initial data provided in **Table 1**, which includes key parameters such as tunnel dimensions, rock properties, and explosive characteristics. This example demonstrates the practical application of the developed methodology for determining borehole placement, charge distribution, and overall explosive consumption. By using this data, it is possible to optimize the blasting design to ensure maximum efficiency and safety during excavation. The methodology is applicable to both oval and circular tunnel cross-sections, providing flexibility for real urban mining conditions. This case illustrates how the proposed approach can be effectively implemented in actual metro construction projects.

The results of the calculation of blasting parameters for the construction of the running tunnel from Shaft No. 16-bis to the "Muzeina" station of the Dnipro Metro, using the developed methodology, are presented in **Table 2**. The calculations include the determination of borehole placement, charge distribution, and the total amount

Table 1: Initial data for calculating blasting parameters for the construction of the running tunnel from Shaft No. 16-bis to the "Muzeina" station of the Dnipro city metro

Name	Unit of measurement	Value
Width of the running tunnel	m	6.0
Height of the running tunnel	m	6.2
Rock compressive strength	MPa	123
Rock density	kg/m^3	2660
Depth of the excavation	m	68
Rock fracturing	-	Highly fractured
Depth of cut (break) boreholes	m	1.8
Depth of blasting boreholes	m	1.6
Depth of contour boreholes	m	1.5
Borehole diameter	m	0.043
Cut type	-	Prismatic
Density of cartridged emulsion explosive Ukrainit-P-SA	kg/m^3	1150
Detonation velocity of cartridged explosive Ukrainit-P-SA	m/s	5050

Table 2: Results of the calculation of blasting parameters for the construction of the running tunnel from Shaft No. 16-bis to the "Muzeina" station of the Dnipro city metro

Name	Unit	Value
Rock structure coefficient, K_{sp}	–	1.1
Structural weakening coefficient of the rock mass, K_s	–	0.4
Rock compaction coefficient, K_u	–	1.003
Calculated specific explosive consumption, q	kg/m^3	1.67
Calculated explosive quantity per face, Q	kg	78.0
Radius of the crushing zone, R_{zm}	m	0.23
Calculated borehole spacing, W	m	0.57
Number of cut (break) boreholes, N_{vr}	pcs	12
Number of production boreholes, N_{vid}	pcs	49
Number of contour boreholes, N_k	pcs	32
Total number of boreholes, N	pcs	93
Average charge per borehole, Q_{sh}	kg	0.84
Mass of cartridged emulsion explosive Ukrainit-P-SA	kg	0.25
Charge amount:		
– for cut borehole, Q_{vr}	kg	1.0
– for production borehole, Q_{vid}	kg	0.75
– for contour borehole, Q_k	kg	1.0
Actual explosive consumption per face, Q_f	kg	75
Charge length with cartridged explosive:		
– cut borehole, $l_{z.vr}$	m	1.12
– production borehole, $l_{z.vid}$	m	0.84
– contour borehole, $l_{z.k}$	m	1.12
Borehole utilization coefficient, η	–	0.95
Actual predicted specific explosive consumption, q_f	kg/m^3	1.71

of explosive required per tunnel face. Each parameter was derived based on the initial data, taking into account rock properties, tunnel dimensions, and the characteristics of the emulsion explosion. The results demonstrate how the methodology can be applied to optimize the excavation process for efficiency and safety. Both cut, production, and contour boreholes were considered in the analysis to ensure complete fragmentation of the rock mass. These results provide a practical example of implementing the proposed blasting design in real metro construction conditions.

Based on the results of the calculation of blasting parameters for the construction of the running tunnel, the layout of the boreholes at the tunnel face was determined. This layout ensures the optimal placement of cut, production, and contour boreholes to achieve efficient rock fragmentation. The arrangement was designed to account for the geometry of the tunnel, the properties of the rock mass, and the characteristics of the explosive used. The resulting borehole pattern is illustrated in **Figure 1**, providing a clear visual representation of the proposed design. This diagram serves as a practical guide for implementing the blasting plan in the field.

By comparing the developed blasting parameters passport with the current passport for the construction of the running tunnel from Shaft No. 16-bis to the "Muzeina" station of the Dnipro Metro, it was found that the calculated BPE parameters using the proposed methodology allow a 14% reduction in the number of boreholes at the tunnel face, from 108 to 93. This indicates that the proposed methodology for calculating blasting parameters optimizes borehole placement at the face by accounting for the physical and mechanical properties of the rock mass and the detonation characteristics of the explosives, resulting in more accurate outcomes.

To verify the parameters calculated with the new methodology, numerical modelling of the stress–strain state of the rock mass under explosive loading is required. One of the most promising approaches for studying the mechanism of explosive rock breakage is the use of numerical modelling based on the finite element method (FEM) (**Babets et al., 2023**). Today, FEM is one of the most advanced modelling techniques, providing a high degree of realism (**Moldabayev et al., 2021**). Numerical modelling allows for the investigation of processes and phenomena that are economically impractical or impossible to study in practice (**Aitkazinova et al., 2022**). Despite the sophistication of mathematical tools and computing technologies, there are relatively few validated software packages capable of accurately simulating the processes occurring during an explosion. In this field, SolidWorks (**Petlovanyi**

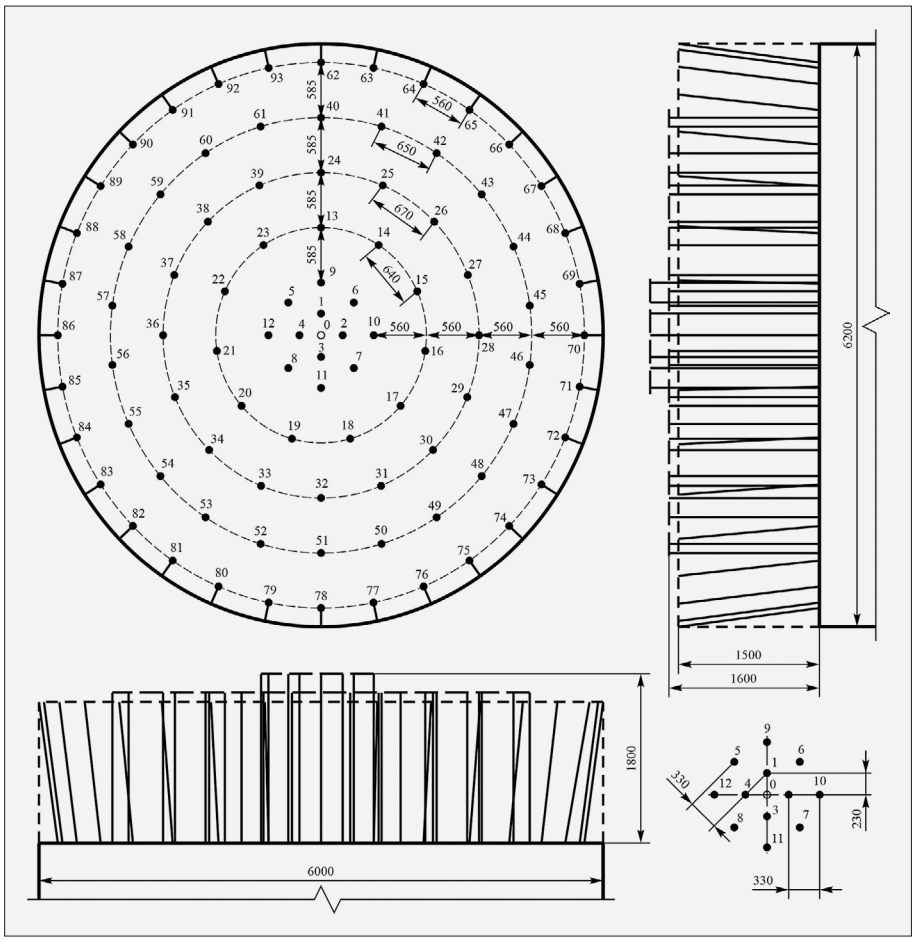


Figure 1: Layout of boreholes at the face of the running tunnel

et al., 2022) and ANSYS (**Smoliński et al., 2021**) are the leading software solutions. Both packages use FEM and are widely applied in mining for modelling the stress–strain state of rock masses under both mining pressure (**Tereshchuk et al., 2018**) and explosive loading (**Kononenko et al., 2024**).

According to the theory of material resistance (**Kyrylenko et al., 2025; Kononenko et al., 2024**), dynamic calculations can be approximated using static calculations with a dynamic coefficient. Therefore, to model the stress–strain state of the rock mass under explosive loading, the licensed SolidWorks Simulation software, available at the Dnipro University of Technology was used. Compared to ANSYS, SolidWorks Simulation reduces the time required for a single computational experiment when solving static problems. At the same time, it is much easier to work with SolidWorks Simulation than with the more complex ANSYS package, which requires a higher level of expertise for problem setup.

The purpose of numerical modelling of the stress–strain state of the rock mass under explosive loading is to verify the calculated blasting parameters for the metro tunnel. The FEM modelling methodology for explosive rock breakage using SolidWorks Simulation included the following stages: creation of the model geometry; definition of the physical and mechanical properties of the model material; setting initial loads, constraints, and mesh; and analysis and processing of results.

During the first stage, the model geometry was created. Since the running tunnel has a width of 6 m and a height of 6.2 m, the model dimensions were set to 30 m in width, height, and depth to eliminate the influence of the model geometry on the simulation results.

The second stage of the modelling involved determining the physical and mechanical properties of the material in the model, including the elastic modulus, Poisson's ratio, shear modulus, density, and the tensile and compressive strength limits. Particular attention was given to accurately representing the real properties of the rock mass, as these parameters govern the propagation of stress waves generated by the explosion. Taking into account the structural composition of the rocks, their fracturing, and the degree of compaction under in-situ stress, the compressive strength of the isotropic model material is determined using a specific analytical expression:

$$\sigma_{st}^{m} = \sigma_{st} \cdot \text{К}_{sp} \cdot \text{К}_{s} \cdot \text{К}_{u}, \text{ MPa}. \quad (33)$$

This approach ensures a more realistic reproduction of the rock mass behavior under loading. In addition, refining these physical and mechanical parameters is es-

Table 3: Average values of the physical and mechanical properties of the model material

Name	Value
Elastic modulus, $\times 10^{10}$ Pa	5.4
Poisson's ratio	0.25
Shear modulus, $\times 10^{10}$ Pa	2.16
Density, kg/m^3	2660
Tensile strength, $\times 10^6$ Pa	5.4
Compressive strength, $\times 10^6$ Pa	54

sential for correctly defining boundary conditions and evaluating the response of the rock mass to explosive forces. Therefore, the second stage of the modelling process forms a critical foundation for obtaining reliable stress–strain calculations.

The adopted average values of the physical and mechanical properties of the model material are presented in **Table 3**. These parameters were determined based on the analysis of the geological characteristics of the rock mass and available experimental data, ensuring their consistency with real conditions. The use of average values simplifies the modelling process while maintaining sufficient calculation accuracy.

According to the next stage of the modelling process, the initial loads, boundary conditions, and the mesh of the model were established. The accuracy of the predicted rock mass failure depends significantly on how correctly these conditions are defined. Since an explosion can be represented as an initial impact followed by the action of explosion-product pressure (**Persson et al., 2018**), a pressure perpendicular to the walls and the tunnel face was applied in all blast holes to simulate this process, taking into account the dynamic coefficient (**Torbica & Lapčević, 2015**). The pressure of the explosion products inside the blast holes, considering the charge diameter, was calculated using the expression:

$$P_m = \frac{\rho \cdot D^2 \cdot К_{dz} \cdot К_d}{8}, \text{ Pa}, \qquad (34)$$

where K_d – the dynamic coefficient.

The computational experiment for determining the change in the stress–strain state of the rock mass at the tunnel face was carried out in the following sequence. First, the geometric model was constructed according to the adopted parameters and the blast hole layout shown in **Figure 1**. Then, in the SolidWorks Simulation environment, a new static analysis was selected. Based on the data presented in **Table 3**, the physical and mechanical properties of the model material were assigned. The Coulomb–Mohr criterion, commonly used for brittle materials with different tensile and compressive properties, was applied as the failure criterion. The model geometry was then fixed, and the explosion-product pressure was applied along the entire length of the blast holes. To avoid the influence of undercharged blast holes on the results,

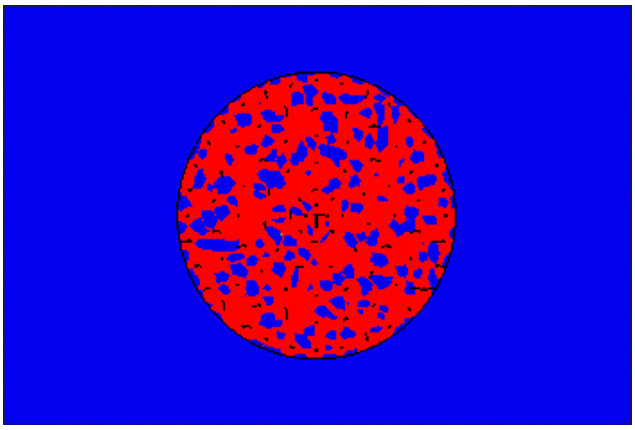


Figure 2: Zones of inelastic deformation formed in the rock mass at the face of the running tunnel under explosive loading

this factor was not considered. The model mesh was generated using curvature-based refinement with high density. Afterward, the computational procedure was launched, and upon completion, the results were refined in the parameter settings. The zones of inelastic deformation that formed in the rock mass at the tunnel face under explosive loading are shown in **Figure 2**.

The areas at the tunnel face where the model material exhibits a safety factor ≤ 1 delineate the zones of rock mass failure under explosive loading. In **Figure 2**, the red regions surrounding the blast holes represent zones of inelastic deformation in the rock mass resulting from the explosion. Analysis of the numerical modelling results of the stress–strain state of the model material at the tunnel face under explosive loading showed that the predicted granulometric composition of the rock after blasting will be less than 0.2 m. This indicates that the use of blasting parameters calculated according to the new methodology for metro tunnel excavation under the specified engineering and geological conditions will prevent the ejection of oversized rock fragments after blasting.

The proposed methodology for calculating blasting parameters in metro tunnel construction has been demonstrated to provide an effective and practical approach for optimizing borehole placement, charge distribution, and overall explosive consumption. Its application to the running tunnel from Shaft No. 16-bis to the "Muzeina" station of the Dnipro Metro allowed a 14% reduction in the number of boreholes while ensuring efficient rock fragmentation, illustrating the method's capability to improve excavation efficiency without compromising safety. The methodology proves versatile, being applicable to both oval and circular tunnel cross-sections and adaptable to a variety of rock mass properties and explosive characteristics. Numerical modelling using the finite element method confirmed that the calculated parameters produce a controlled stress–strain response in the rock mass and result in a predictable granulometric composition of less than 0.2 m. These simulations demonstrate

that the approach effectively prevents oversized rock fragments from being ejected, enhancing operational safety and reliability. Overall, the combination of analytical calculation and numerical verification confirms that the proposed methodology is robust, reliable, and suitable for practical implementation in metro tunnel construction under complex engineering and geological conditions.

5. Discussion of Research Results

The proposed methodology for calculating blasting parameters in metro tunnel construction provides a structured and practical approach for optimizing excavation processes. By applying the methodology to the running tunnel from Shaft No. 16-bis to the "Muzeina" station of the Dnipro Metro, key parameters such as borehole placement, charge distribution, and total explosive consumption were determined in a way that ensures both efficiency and safety. The initial data, including tunnel dimensions, rock properties, and explosive characteristics, allowed for precise tailoring of the blasting design to the specific geological conditions of the site, demonstrating the methodology's applicability in real-world urban mining projects.

Static FEM analysis with a dynamic coefficient provides only an approximate representation of explosive loading, as it cannot explicitly capture the transient nature of shock-wave propagation and high strain-rate effects associated with detonation. The approach assumes an equivalent quasi-static load, which neglects wave reflections, stress superposition, and time-dependent energy dissipation in the rock mass. Material behaviour is typically described using linear or simplified nonlinear constitutive models, limiting the accurate simulation of fracture initiation, crack propagation, and progressive damage under dynamic loading. In addition, the use of a dynamic coefficient requires prior assumptions or calibration, which introduces uncertainty and reduces generality across different geological conditions. Consequently, such modelling should be regarded as a verification and comparative tool for stress–strain trends and deformation zones, rather than a substitute for fully coupled dynamic or explicit blast simulations.

Comparison with the existing blasting passport revealed that the proposed approach reduces the total number of boreholes at the tunnel face by 14%, from 108 to 93, without compromising rock fragmentation. This reduction reflects the optimization achieved by accounting for the physical and mechanical properties of the rock mass as well as the detonation characteristics of the explosives. The methodology ensures that cut, production, and contour boreholes are arranged to maximize energy efficiency while maintaining safety standards, thereby reducing unnecessary drilling and explosive consumption.

Numerical modelling using the finite element method (FEM) in SolidWorks Simulation further verified the calculated blasting parameters. The simulation allowed for a detailed analysis of the stress–strain state of the rock mass under explosive loading, taking into account boundary conditions, pressure distribution, and rock material properties (**Babets et al., 2023; Brand, 2011**). The results indicated controlled inelastic deformation zones and a predictable granulometric composition of fragmented rock, demonstrating that the proposed blasting design produces the desired breakage without ejecting oversized rock fragments. This validation highlights the methodology's reliability and reinforces its practical utility.

The versatility of the methodology is evident in its applicability to different tunnel cross-sections, including both oval and circular profiles, and its adaptability to varying rock mass characteristics and explosive types. By integrating both analytical calculations and numerical verification, the approach provides a comprehensive framework for designing safe and efficient blasting operations (**Pankratova et al., 2024b; Kononenko et al., 2023a; Gu & Cao, 2023**). The combined use of precise calculation and simulation ensures that the excavation process is optimized for both energy efficiency and operational control.

The proposed adapted methodology for calculating the parameters of drilling and blasting operations for the construction of interstation tunnels has been tested under real operating conditions. The approbation was carried out during the development of underground mine workings at the mines of PJSC "Zaporizhzhia Iron Ore Combine" (**Kononenko et al., 2023a**). The methodology was applied to full-scale industrial blasting operations rather than laboratory or numerical simulations. This allowed the reliability and practical applicability of the proposed approach to be evaluated under complex geological and mining conditions. The obtained results confirm the feasibility of using the methodology in real tunnel construction and mining practice.

Overall, the results confirm that the proposed methodology is robust, reliable, and suitable for practical implementation in metro tunnel construction under complex engineering and geological conditions. The significant reduction in borehole numbers, the predictability of rock fragmentation, and the controlled stress–strain response achieved through numerical modelling all demonstrate that the approach enhances operational safety, reduces material and labor costs, and provides a reproducible framework for similar projects. This combination of analytical and computational methods establishes a strong foundation for improved planning and execution of urban tunneling operations.

6. Conclusions

The present study has proposed and validated a novel methodology for calculating blasting parameters in the construction of metro running tunnels, with application to the Dnipro Metro line from Shaft No. 16-bis to the "Muzeina" station. Analysis of existing approaches for under-

ground excavation highlighted that the most effective strategy combines the determination of specific explosive consumption with the assessment of deformation zones formed around each borehole (**Pankratova et al., 2024b; Kononenko et al., 2023a**). This integrated approach ensures a more accurate, safe, and resource-efficient design for blasting operations in complex urban mining conditions. The developed methodology introduces a fundamentally new framework for designing borehole placement and charge distribution in metro tunnels (**Kononenko et al., 2023a; Gu & Cao, 2023**). It is based on grouping boreholes according to their occupied area at the tunnel face and their arrangement along the contour (**Ma et al., 2019; Yuan, 2011**). Critical factors, including the radius of intensive rock fragmentation, borehole and charge diameters, explosive pressure, rock compressive strength, structural composition, fracturing, and compaction under overburden stress, are explicitly accounted for. Each borehole is assigned a precisely calculated charge, ensuring optimal rock fragmentation while minimizing unnecessary energy expenditure and reducing operational risks.

Validation through numerical modelling using the finite element method (FEM) confirmed the robustness of the methodology. Simulations of the stress–strain state of the rock mass under explosive loading demonstrated controlled the formation of inelastic deformation zones, with a predicted post-blast granulometric composition of less than 0.2 m. These results indicate that the proposed methodology effectively prevents the ejection of oversized rock fragments, enhances operational safety, and ensures predictable rock breakage. Implementation of the new parameters led to a rationalized layout of boreholes, achieving a 14% reduction in the total number of boreholes at the tunnel face compared to the existing blasting passport. This reduction demonstrates the methodology's potential for significant resource savings and operational efficiency without compromising the quality of rock fragmentation. The approach is versatile, applicable to both oval and circular tunnel cross-sections, and adaptable to varying rock mass properties and explosive types, making it suitable for a wide range of urban tunnelling projects.

Overall, the combination of analytical calculation, empirical consideration of rock properties, and numerical verification establishes a comprehensive, reliable, and practical framework for metro tunnel blasting design. The methodology provides an effective tool for optimizing excavation efficiency, reducing material and labor costs, and enhancing safety and predictability in underground construction projects. These findings offer a reproducible and scientifically grounded basis for the planning and execution of metro tunnelling operations under complex engineering and geological conditions.

Acknowledgment

The presented work contains the results of the research project DT-530 "Scientific substantiation and development of georeactor systems for the integrated processing of coal preparation waste with a focus on the recovery of critical raw materials", carried out with the support of the Ministry of Education and Science of Ukraine.

Funding

This work was conducted within the framework of the project "European Mining Regions Innovation Ecosystems Supporting Circularity and Resource Efficiency (EMRIE)" under the INTERREG Programme (project ID: 03C1069).

7. References

Aitkazinova, S., Sdvyzhkova, O., Imansakipova, N., Babets, D., & Klymenko, D. (2022). Mathematical modeling the quarry wall stability under conditions of heavily jointed rocks. Nau*kovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (6), 18–24. https://doi.org/10.33271/nvngu/2022-6/018

Alkhdour, A., Yasin, A. A., & Tiutkin, O. (2023). Rational design solutions for deep excavations using soil nail wall systems. *Mining of Mineral Deposits, 17*(3), 110–118. https://doi.org/10.33271/mining17.03.110

Andrievskii, A. (1993). Calculation of optimal parameters for drill-and-blast operation chart in mining with direct slot stage cutting. *Journal Of Mining Science, 28*(5), 456-461. https://doi.org/10.1007/bf00711129

Avanoğlu-Çetin, B., & Öztürk, Ö. (2019). Reflecting the art, culture and history into the interior design of underground metro stations, case study: Dnipro metro extension line. *Tunnels and Underground Cities: Engineering and Innovation Meet Archaeology, Architecture and Art*, 3–11. https://doi.org/10.1201/9780429424441-1

Babets, D., Sdvyzhkova, O., Hapieiev, S., Shashenko, O., & Vasyl, V. (2023). Multifactorial analysis of a gateroad stability at goaf interface during longwall coal mining – A case study. *Mining of Mineral Deposits, 17*(2), 9–19. https://doi.org/10.33271/mining17.02.009

Bashynska, I., Niekrasova, L., Ivliev, D., Dudek, M., Kosenkov, V., & Yakimets, A. (2024). Justification for Transitioning Equipment to Direct Current for Smart Small Enterprises with Sustainable Solar Power Autonomy. *2024 IEEE 5th KhPI Week on Advanced Technology (KhPIWeek)*, 1–6. https://doi.org/10.1109/khpiweek61434.2024.10878001

Bozic, B., & Strelec, S. (2020). Tectonic fabric and determination of drilling geometry for blasting. *Rock Fragmentation by Blasting*, 443–443. https://doi.org/10.1201/9781003078104-66

Brand, M. (2011). Beispiele zur zusammengesetzten Beanspruchung. *Grundlagen FEM Mit SolidWorks 2010*, 62–75. https://doi.org/10.1007/978-3-8348-9838-8_3

Brown, L., & Hudyma, M. (2016). Identification of Stress Change Within a Rock Mass Through Apparent Stress of Local Seismic Events. *Rock Mechanics and Rock Engineering*, 50(1), 81–88. https://doi.org/10.1007/s00603-016-1092-z

Carlos, L. J., Emilio, L. J., Francisco, J. A. C., & Yvonne Visser de, R. (2017). Mechanized systems for charging and dewatering blastholes. *Drilling and Blasting of Rocks*, 144–153. https://doi.org/10.1201/9781315141435-15

Cheberiachko, S., Yavorska, O., Deryugin, O., Lantukh, D., Bas, I., Kruzhilko, O., & Melnyk, V. (2023). Improving Safety of Passenger Road Transportation. *Transactions on Transport Sciences, 14*(2), 11–20. https://doi.org/10.5507/tots.2023.003

Fedoreiko, V. S., Luchko, M. R., Iskerskyi, I. S., & Zahorodnii, R. I. (2019). Enhancing the efficiency of energy generation systems based on solid biofuels: technical and economic aspects. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, 2, 94–100. https://doi.org/10.29202/nvngu/2019-2/14

Fedoreiko, V., Zahorodnii, R., Lutsyk, I., Rutylo, M., & Bureha, N. (2025). Modelling of resource-saving control modes of a bioheat generator using neuro-fuzzy controllers. *IOP Conference Series: Earth and Environmental Science*, 1457(1), 012005. https://doi.org/10.1088/1755-1315/1457/1/012005

Gheorghiosu, E., & Becuţ, S. (2024). Design and Execution of Drilling and Blasting Works Using Modern Scanning Techniques. *Mining Revue*, 30(s1), 70–77. https://doi.org/10.2478/minrv-2024-0042

Gu, Z., & Cao, M. (2023). Analysis of unstable block by discrete element method during blasting excavation of fractured rock mass in underground mine. *Heliyon*, 9(11), e22558. https://doi.org/10.1016/j.heliyon.2023.e22558

Haiko, H., Savchenko, I., & Haiko, Y. (2023). Functional Planning Optimization of Exploiting Underground Space in Large Cities Using System Methodology. *System Analysis and Artificial Intelligence*, 43–61. https://doi.org/10.1007/978-3-031-37450-0_3

Kholodenko, T., Ustimenko, Y., Pidkamenna, L., & Pavlychenko, A. (2014). Ecological safety of emulsion explosives use at mining enterprises. *Progressive Technologies of Coal, Coalbed Methane, and Ores Mining*, 255-260. http://doi.org/10.1201/b17547-45

Kholodenko, T., Ustimenko, Y., Pidkamenna, L., & Pavlychenko, A. (2015). Technical, economic and environmental aspects of the use of emulsion explosives by ERA brand in underground and surface mining. *New Developments in Mining Engineering 2015*, 211-219. http://doi.org/10.1201/b19901-38

Khomenko, O., Kononenko, M., Myronova, I., & Savchenko, M. (2019). Application of the emulsion explosives in the tunnels construction. *E3S Web of Conferences, 123*, 01039. https://doi.org/10.1051/e3sconf/201912301039

Khomenko, O., Rudakov, D., & Kononenko, M. (2011). Automation of drill and blast design. *Technical and Geoinformational Systems in Mining*, 271–275. https://doi.org/10.1201/b11586-45

Kononenko M., Khomenko O., Kovalenko I., & Savchenko M. (2021). Control of density and velocity of emulsion explosives detonation for ore breaking. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (2), 69-75. https://doi.org/10.33271/nvngu/2021-2/069

Kononenko M., Khomenko O., Kovalenko I., Kosenko A., Zagorodnii R., Dychkovskyi R. (2023c). Determining the performance of explosives for blasting management. *Rudarsko-Geološko-Naftni Zbornik, 38*(3), 19–28. https://doi.org/10.17794/rgn.2023.3.2

Kononenko M., Khomenko O., Sadovenko I., Sobolev V., Pazynich Yu., Smolinski A. (2023b). Managing the rock mass destruction under the explosion. *Journal of sustainable mining, 22*(3), 240-247. https://doi.org/10.46873/2300-3960.1391

Kononenko, M., Khomenko, O., Cabana, E., Mirek, A., Dyczko, A., Prostański, D., Dychkovskyi, R. (2023a). Using the methods to calculate parameters of drilling and blasting operations for emulsion explosives. Acta Montanistica Slovaca, 28(3), 655–667. https://doi.org/10.46544/ams.v28i3.10

Kononenko, M., Khomenko, O., Kosenko A., Myronova I., Bash V. & Pazynich Yu. (2024). Raises advance using emulsion explosives. *E3S Web of Conferences, 526*, 01010. https://doi.org/10.1051/e3sconf/202452601010

Kosenko, A., Khomenko, O., Kononenko, M., Polyanska, A., Buketov, V., Dychkovskyi, R., Polański, J., Howaniec, N., & Smolinski, A. (2025). Sustainable management of iron ore extraction processes using methods of borehole hydro technology. *International Journal of Mining and Mineral Engineering,* 16(1), 92–112. https://doi.org/10.1504/ijmme.2025.145592

Krysin, R.S., Ishchenko, N.I., Klimenko, V.A., Piven, V.A., & Kuprin, V.P. (2004). Explosive ukranit-PM-1: Equipment and fabrication technology. *Gornyi Zhurnal*, (8), 32-37.

Kyrylenko, O., Denysiuk, S., Bielokha, H., Dyczko, A., Stecuła, B., & Pazynich, Y. (2025). Smart Monitoring and Management of Local Electricity Systems with Renewable Energy Sources. *Energies*, 18(16), 4434. https://doi.org/10.3390/en18164434

Listh, O. (1978). Setback Testing of ANFO and Water-Based Explosives. *Propellants, Explosives, Pyrotechnics*, 3(1–2), 36–41. Portico. https://doi.org/10.1002/prep.19780030111

Lyashenko, V., Vorob'ev, A., Nebohin, V., Vorob'ev, K. (2018). Improving the efficiency of blasting operations in mines with the help of emulsion explosives. *Mining of Mineral Deposits, 12*(1), 95-102. https://doi.org/10.15407/mining12.01.095

Ma, X., Westman, E., Malek, F., & Yao, M. (2019). Stress Redistribution Monitoring Using Passive Seismic Tomography at a Deep Nickel Mine. Rock Mechanics and Rock Engineering, 52(10), 3909–3919. https://doi.org/10.1007/s00603-019-01796-7

Mishra, A. (2012). Rapid excavation of tunnels using innovative drilling and blasting techniques. Tunneling in Rock by Drilling and Blasting, 15–22. https://doi.org/10.1201/b13762-4

Moldabayev, S. K., Sdvyzhkova, O. O., Babets, D. V., Kovrov, O. S., & Adil, T. K. (2021). Numerical simulation of the open pit stability based on probabilistic approach. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (6), 29–34. https://doi.org/10.33271/nvngu/2021-6/029

Morelli, G. L. (2015). Empirical Assessment of the Mean Block Volume of Rock Masses Intersected by Four Joint

Sets. Rock Mechanics and Rock Engineering, 49(5), 1759–1771. https://doi.org/10.1007/s00603-015-0882-z

Myronova, I. (2015). The level of atmospheric pollution around the iron-ore mine. *New Developments in Mining Engineering 2015*, 193-197. http://doi.org/10.1201/b19901-35

Myronova, I. (2016). Prediction of contamination level of the atmosphere at influence zone of iron-ore mine. *Mining of Mineral Deposits, 10*(2), 64-71. http://doi.org/10.15407/mining10.02.0064

Pankratova, N., Haiko, H., & Savchenko, I. (2024a). The Concept of System Approach to Mastering Underground Space of Large Cities. *Modeling the Underground Infrastructure of Urban Environments*, 25–48. https://doi.org/10.1007/978-3-031-47522-1_2

Pankratova, N., Haiko, H., & Savchenko, I. (2024b). Evaluating Ecological Risks of Underground Transport Infrastructure Development Using BOCR. *Modeling the Underground Infrastructure of Urban Environments*, 175–188. https://doi.org/10.1007/978-3-031-47522-1_5

Pankratova, N., Haiko, H., & Savchenko, I. (2024c). Strategy of Evaluation and Risk Management in Practical Urban Development Problems. *Modeling the Underground Infrastructure of Urban Environments*, 97–173. https://doi.org/10.1007/978-3-031-47522-1_4

Persson, P.-A., Holmberg, R., & Lee, J. (2018). *Rock Blasting and Explosives Engineering*. https://doi.org/10.1201/9780203740514

Petlovanyi, M., Lozynskyi, V., Saik, P., & Sai, K. (2019). Predicting the producing well stability in the place of its curving at the underground coal seams gasification. *E3S Web of Conferences*, 123, 01019. https://doi.org/10.1051/e3sconf/201912301019

Petrenko, V., Bondarenko, N., Miroshnyk, V., Burskyi, M., & Konoval, V. (2023). Substantiating parameters of short-delay blasting and seismic safety while constructing the inclined tunnel. *IOP Conference Series: Earth and Environmental Science, 1156*(1), 012010. https://doi.org/10.1088/1755-1315/1156/1/012010

Petrenko, V., Tiutkin, O., Heletiuk, I., & Tkach, T. (2020). The new approach in evaluating the mechanism of the blast effect and organizing the blasting operations while tunneling. *E3S Web of Conferences, 168*, 00034. https://doi.org/10.1051/e3sconf/202016800034

Pivnyak, G., Stepanenko, Y., Stecuła, K., Kyrychenko, M., Lysenko, O., Dychkovskyi, R. (2025) Management of Zero-Sequence Parameters for Earth Faults on the Power Receiver's Side in IT-Type Networks. *Energies*, 18, 6407. https://doi.org/10.3390/en18246407

Polyanska, A., Pazynich, Y., Petinova, O., Nesterova, O., Mykytiuk, N., & Bodnar, G. (2024). Formation of a Culture of Frugal Energy Consumption in the Context of Social Security. The Journal of the International Committee for the History of Technology, 29(2), 60–87. https://doi.org/10.11590/icon.2024.2.03

Polyanska, A., Sala, D., Psyuk, V., & Pazynich, Y. (2025). A Multicriteria Approach to the Study of the Energy Transition Results for EU Countries. *Energies*, 18(20), 5406. https://doi.org/10.3390/en18205406

Pyzalski, M., Juszczyk, M., Durczak, K., Sala, D., Duda, J., Dudek, M., & Ustinovičius, L. (2025). Cement Carbonation Under Fermentation Conditions as a Tool for CO2 Emission Management-Technological, Environmental and Economic Analysis. *Energies*, 18(17), 4588. https://doi.org/10.3390/en18174588

Radkevych, A., Tiutkin, O., Kuprii, V., & Bielikova, S. (2022). The comparative analysis of the stress-strain state of the support of the escalator tunnel constructed in weak soils by the NATM. *IOP Conference Series: Earth and Environmental Science, 970*(1), 012002. https://doi.org/10.1088/1755-1315/970/1/012002

Sala, D., & Richert, M. (2025). Perspectives of Additive Manufacturing in 5.0 Industry. Materials, 18(2), 429. https://doi.org/10.3390/ma18020429

Serdaliyev, Y., & Iskakov, Y. (2022). Research into electrohydraulic blasting impact on ore masses to intensify the heap leaching process. *Mining of Mineral Deposits*, 16(1), 52–57. https://doi.org/10.33271/mining16.01.052

Shcherba, A., Podoltsev, O., Kucheriava, I., Hutorova, M., Petryshyn, L., & Pazynich, Y. (2025). Computer simulation and management of partial discharges in XLPE insulation of high-voltage power cable. *Polityka Energetyczna – Energy Policy Journal*, 28(3), 5–26. https://doi.org/10.33223/epj/208278

Smoliński, A., Malashkevych, D., Petlovanyi, M., Rysbekov, K., Lozynskyi, V., & Sai, K. (2022). Research into Impact of Leaving Waste Rocks in the Mined-Out Space on the Geomechanical State of the Rock Mass Surrounding the Longwall Face. *Energie*s, 15(24), 9522. https://doi.org/10.3390/en15249522

Tereshchuk, R.M., Khoziaikina, N.V., & Babets, D.V. (2018). Substantiation of rational roof-bolting parameters. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (1), 19–26.

Torbica, S., & Lapčević, V. (2015). Estimating extent and properties of blast-damaged zone around underground excavations. *Rem: Revista Escola de Minas, 68*(4), 441–453. https://doi.org/10.1590/0370-44672015680062

Vladyko, O., Maltsev, D., Gliwiński, Ł., Dychkovskyi, R., Stecuła, K., & Dyczko, A. (2025). Enhancing Mining Enterprise Energy Resource Extraction Efficiency Through Technology Synthesis and Performance Indicator Development. *Energies*, 18(7), 1641. https://doi.org/10.3390/en18071641

Yuan, W. (2011). Rapid excavation technology by drilling and blasting and it's application in hard rock roadway. *2011 International Conference on Multimedia Technology*, 6479–6483. https://doi.org/10.1109/icmt.2011.6003271

Zhang, Z., Yao, Y., Jiang, N., Xie, Q., & Wang, J. (2024). Theoretical study of the vibration characteristic in geological layer under blasting excavation of metro tunnel. *Journal of Vibration and Control*, 10775463241274589. https://doi.org/10.1177/10775463241274589

SAŽETAK

Upravljanje rizicima u izgradnji gradskih prometnih tunela primjenom emulzijskih eksploziva: studija slučaja

U ovome radu predlaže se metodologija za proračun parametara bušačko-minerskih radova u izgradnji gradskih prometnih tunela uporabom emulzijskih eksploziva u okviru integriranoga sustava upravljanja rizicima. Bušačko-minerski radovi u urbanim tunelima zahtijevaju visoku preciznost projektiranja minskih bušotina kako bi se osigurala stabilna fragmentacija stijenske mase i smanjili tehnički i operativni rizici. Cilj istraživanja jest razviti metodologiju temeljenu na upravljanju rizicima za proračun parametara bušačko-minerskih radova u tunelima temeljem racionalnoga prostornog rasporeda bušotina i kontrolirane fragmentacije stijena. Predložena metodologija zasniva se na teoriji elastičnosti te kvazistatičkim i valno-temeljenim hipotezama loma stijena pod djelovanjem eksplozivnoga naprezanja. Minske bušotine raspoređene su u grupe prema površinama čela tunela, primjenom načela konturiranoga povlačenja. Linije pravca loma projektirane su na temelju radijusa zone drobljenja, nakon čega slijede proračuni linije najmanjega otpora, potrošnje eksploziva, razmaka bušotina, količine punjenja po bušotini i ukupne potrošnje eksploziva. Geometrija minskih bušotina definirana je potencijskim zakonom, koji povezuje tlak eksplozije, promjer bušotine, jednoosnu tlačnu čvrstoću stijene, strukturu i ispucalost stijenske mase te geostatičke uvjete naprezanja. Numeričke simulacije potvrdile su formiranje stabilnih zona neelastičnih deformacija i ujednačenu fragmentaciju stijenske mase, znatno smanjujući pojavu prevelikih blokova na čelu tunela. Metodologija integrira analitičke proračune miniranja s numeričkim modeliranjem stanja naprezanja i deformacija stijenske mase unutar jedinstvenoga okvira upravljanja rizicima u gradskim tunelima. Primjena predložene metodologije povećava učinkovitost i sigurnost miniranja, omogućuje do 14 % uštede u resursima iskopa te smanjuje tehničke i operativne rizike povezane s bušačko-minerskim radovima u urbanim podzemnim građevinskim zahvatima.

Ključne riječi:
bušačko-minerski radovi, emulzijski eksplozivi, modeliranje stanja naprezanja i deformacija, lom stijenske mase, učinkovitost tunelskoga iskopa

Author's contribution

Maksym Kononenko (Doctor of Engineering, Professor) - conceptualization, methodology, formal analysis, original draft; **Oleh Khomenko** (Doctor of Engineering, Professor) - supervision, data validation, review & editing; **Serhii Hapieiev** (Doctor of Engineering, Professor) - data curation, software support, results visualization & investigation; simulation, technical validation; **Roman Tereshchuk** (Doctor of Engineering, Professor) - environmental assessment, editing and proofreading; **Roman Dychkovskyi** (Doctor of Engineering, Professor): - overall supervision, literature review, mechanical modeling, finite element.