RGNZ/MGPB

Management of Frame-Anchor Fastening Parameters for Preparatory Excavations in Monorail-Based Heavy Cargo Delivery

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
DOI: 10.17794/rgn.2026.2.12

Original scientific paper

Andrii Herasymenko[1], **Leonid Shyrin**[1], **Rostyslav Yegorchenko**[1],
Ivan Iniutkin[1], **Yuliya Pazynich**[2,3]*

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

[2] *AGH University of Krakow, Faculty of Management, al. Mickiewicza 30, Krakow, 30059, Poland.*

[3] *Dnipro University of Technology, Department of philosophy and pedagogy, 19 Yavornytskoho Ave., 49-005, Dnipro, Ukraine.*

Abstract

This article presents a comprehensive study on the management and optimization of frame-anchor support systems for seam preparatory excavations designed for the transportation of large-tonnage cargo via suspended monorail transport. With the intensification of underground mining operations and the increasing use of heavy mechanized transport, ensuring the stability and safety of mine workings under dynamic load conditions has become a critical challenge for engineering. The research proposes an innovative support technology based on the combined fastening of monorail systems to the crowns of metal arches and directly to the roof using deep-embedded anchors. This approach aims to reduce dynamic impacts on the excavation roof and improve the overall reliability of the support system. To evaluate the effectiveness of the proposed support design, a numerical modelling method was employed to simulate the interaction of components within the dynamic system "suspended monorail – support – rock mass." The stress-strain behaviour of the frame-anchor structure under real load scenarios was analyzed using SolidWorks Simulation software. During the simulation, various parameters were systematically varied, including the spacing of support frames, the length and anchorage depth of the rock bolts, and the mechanical properties of the surrounding rock mass. The results of the analysis enabled the identification of rational design parameters that minimize deformation and enhance load-bearing capacity. In particular, optimal combinations of frame spacing and anchor configurations were found to significantly reduce stress concentrations and improve the stability of preparatory workings under dynamic loading from moving monorail trains. The study demonstrates that effective management of support system parameters can lead to improved safety, reduced material consumption, and faster development of mining panels. The findings have practical significance for the design of underground transport routes and can be incorporated into normative documents governing support systems in dynamically loaded mine environments.

Keywords:
Frame-anchor fastening, Monorail transportation, Heavy cargo delivery, Stress–strain analysis, Mining infrastructure managemen, Dynamic load distribution

1. Introduction

The implementation of suspended monorail tracks as the primary transportation system in the development of mineral deposits plays a crucial role in accelerating the progress of seam-level district excavations (**Herasymenko et al., 2023**). This method enhances logistical efficiency and reduces the time required for preparatory operations (**Rastsvietaiev et al., 2015**). However, when monorail systems are mounted using traditional fastening schemes, typically attached directly to arch supports, the dynamic behaviour of the surrounding rock mass under stress becomes a significant concern. Intense deformation of the rock mass can lead to alterations in the stress distribution, which, in turn, negatively impacts the technical condition and reliability of the transportation infrastructure (**Herasymenko et al., 2023; Rastsvietaiev et al., 2015; Kononenko et al., 2024**). As a result, effective management of support systems becomes essential to maintain the stability and safety of both the monorail structures and the surrounding excavation (**Babets et al., 2023**). An optimized management approach should include continuous monitoring, adaptive reinforcement strategies, and the integration of innovative fastening technologies to ensure consistent performance under variable geological and loading conditions (**Rastsvietaiev et al., 2015; Aitkazinova et al., 2022**).

* Corresponding author: Yuliya Pazynich
e-mail address: jpazynich@ukr.net

Received: 8 September 2025. Accepted: 1 November 2025.
Available online: 13 March 2026

Studies (**Herasymenko et al., 2023**) have shown that the transportation of large-tonnage cargo along deformed monorail tracks generates dynamic loads that can lead to the failure of arch supports and even roof collapses. These loads intensify the degradation of structural elements and significantly compromise the safety of underground workings. Under conditions of intensified mining operations, traditional technological schemes for auxiliary transportation prove to be particularly vulnerable to changes in the geomechanical environment (**Rastsvietaiev et al., 2015; De Borst et al., 2012**). Their limited adaptability to evolving stress conditions and deformation zones makes them unsuitable for high-performance and safe mining systems (**Rastsvietaiev et al., 2015; Tereshchuk et al., 2018**). Effective management of transportation infrastructure is essential, requiring a proactive approach to monitoring, maintenance, and reinforcement of support systems (**Aitkazinova et al., 2022; De Borst et al., 2012; Tereshchuk et al., 2018; Khomenko et al., 2023**). To address these challenges, innovative technical solutions must be developed and implemented to enhance the structural resilience, operational stability, and adaptability of monorail-based transport systems under dynamic loading conditions (**Herasymenko et al., 2023; Rastsvietaiev et al., 2015; Tereshchuk et al., 2018; Khomenko et al., 2023; Bondarenko et al., 2021**).

One of the critical tasks is the safe and efficient transportation of large-tonnage equipment, such as sections of mechanized roof supports, shearer components, and other heavy machinery, to designated installation chambers (**Rastsvietaiev et al., 2015; Khomenko et al., 2018**). Traditional transportation methods, particularly overground rail systems, often lack the necessary flexibility and adaptability to function effectively under such conditions (**Bondarenko et al., 2021; Khomenko et al., 2018; Kononenko et al., 2023**). Their performance is typically constrained by irregular layouts, limited turning radii, and unstable ground surfaces inherent to the mine environment (**Herasymenko et al., 2023; Kononenko et al., 2024; Zienkiewicz et al., 2013**). This lack of adaptability can lead to delays, increased labor costs, and heightened safety risks for personnel and equipment. Feasibility of implementing such innovative solutions is particularly relevant during the preparation of new mining panels, as well as during installation and dismantling operations (**Kononenko & Khomenko, 2010**). These stages of mine development involve complex logistical challenges and increased operational risks, especially in confined underground environments. Therefore, the management of transportation systems in these critical phases must focus on adopting more resilient and adaptable technologies, such as suspended monorail systems, to ensure operational continuity and safety.

In international mining practice, the development of coal seams using high-performance mining complexes encounters similar challenges related to transportation and infrastructure stability (**Rastsvietaiev et al., 2015**). These challenges are typically addressed by introducing alternative types of auxiliary transportation and implementing methods to maintain their technical condition in response to specific geological and operational conditions (**Rastsvietaiev et al., 2015; Moldabayev et al., 2021**). Ensuring the continuous functionality of transportation systems under dynamic mining environments is critical for both productivity and safety (**Kononenko & Khomenko, 2010; Moldabayev et al., 2021; Kovalevska et al., 2020**). One of the most promising developments in this area is the adoption of suspended monorail diesel locomotives, which offer enhanced maneuverability and load-bearing capacity in confined underground spaces (**Khomenko et al., 2023**; **Yegorchenko et al., 2022**). To ensure their effective application, it is essential to evaluate their operational performance based on the integrated behaviour of components within the transport-technological system "suspended monorail – mine support – rock mass." Such system-level analysis allows for the rational management of technical parameters and supports the development of robust, adaptive transportation infrastructure in modern mining operations.

It has been experimentally confirmed that, at present, the interaction parameters between the components of the technological system "suspended monorail – mine support – rock mass" remain insufficiently studied and poorly understood (**Herasymenko et al., 2023**). This knowledge gap limits the ability to predict system behaviour under varying mining conditions and complicates the development of effective transport management strategies (**Sala & Bieda, 2021**). As mining operations become more dynamic and equipment loads increase, the lack of comprehensive data on these interactions poses risks to both infrastructure integrity and operational safety (**Rastsvietaiev et al., 2015**; **Khomenko, Kononenko & Bilegsaikhan, 2018**). The issues of operational monitoring of the technical condition of suspended monorail tracks in district workings are of critical importance. Particular attention must be given to determining the maximum allowable dynamic loads that the system can safely withstand under real underground conditions (**Falshtynskyi et al., 2020**). Addressing these challenges requires a combination of in-situ field observations, numerical modelling, and theoretical justification to develop reliable criteria for design, maintenance, and safety management (**Herasymenko et al., 2023; Rastsvietaiev et al., 2015; Babets et al., 2023; Vlasov et al., 2022**).

Based on in-mine research into the interaction between suspended monorail components and arch supports, it was established that zones of deformed roof rock tend to form around the crowns of load-bearing arches to which the monorail system is attached during the transportation of large-tonnage cargo through seam-level district workings (**Rastsvietaiev et al., 2015**).

These deformations compromise both the structural integrity of the support system and the safety of underground operations (**Kosenko et al., 2025**). The primary cause of such deformation has been identified as dynamic loading, particularly at the joints between monorail beams and in sections of the track characterized by alternating elevation profiles (**Babets et al., 2023; Khomenko et al., 2023; Yegorchenko et al., 2022; Kosenko et al., 2025**). These areas are especially prone to stress, concentration and fatigue due to the uneven distribution of loads (**Babets et al., 2023; Bondarenko et al., 2021; Moldabayev et al., 2021; Kovalevska et al., 2020; Kononenko et al., 2016**). Additionally, emergency braking scenarios introduce sudden dynamic overloads, which are transferred from the monorail beams to the arch supports, exacerbating structural instability (**Babets et al., 2023; Kovalevska et al., 2020; Tokarczyk, 2016**). The comprehensive understanding of these interactions is essential for the effective management and design of support systems capable of withstanding the operational demands of modern monorail transport in underground mining environments (**Rastsvietaiev et al., 2015; Khomenko et al., 2023; Lewicka & Lewicka, 2019**).

Such disturbances in the technical condition of the monorail support, along with increased dynamic loads on the arch supports and surrounding rock mass, have a negative impact on the transportation process and reduce the throughput capacity of haulage workings. Therefore, the aim of this study is to develop innovative technological schemes involving combined frame-anchor support for preparatory workings and an improved monorail support system for suspended monorails. The objective is to justify and determine the optimal parameters of these systems to ensure the safe and efficient transportation of large-tonnage cargo under complex and dynamic operational conditions.

Literature Review on Frame-Anchor Fastening Parameters for Preparatory Excavations in Monorail-Based Heavy Cargo Transportation.

Efficient management of underground mining operations critically depends on the stability and reliability of preparatory excavations, especially when heavy cargo transport is involved (**Rastsvietaiev et al., 2015; Vladyko et al., 2025**). Frame-anchor fastening systems have emerged as a fundamental component in maintaining the structural integrity of mine workings subjected to dynamic loads from suspended monorail transport (**Herasymenko et al., 2023; Rastsvietaiev et al., 2015; Khomenko et al., 2018; Kumbasaroglu, 2010**). Studies emphasize the importance of optimizing fastening parameters, such as anchor length, spacing, and depth, to ensure load distribution and prevent excessive deformation or failure of supports (**Kononenko & Khomenko, 2010; Mackiewicz et al., 2022**). Effective mine management integrates monitoring of these parameters to minimize downtime and enhance safety during material handling operations (**Dychkovskyi et al., 2024**).

The transportation of large-tonnage cargo via suspended monorail systems generates complex dynamic loads that interact with the rock mass and support structures (**Kononenko & Khomenko, 2010; Kang et al., 2020**). Research has shown that traditional fastening schemes may not adequately address the dynamic effects, leading to accelerated wear and failure of arch supports and anchors (**Kononenko & Khomenko, 2010; Moldabayev et al., 2021; Kang et al., 2020; Carrascal et al., 2007**). Consequently, investigations focus on developing combined fastening techniques, such as frame-anchor systems, that better absorb and redistribute stress (**Kang et al., 2020; Carrascal et al., 2007; Dychkovskyi et al., 2024**). These studies highlight the need for adaptive support designs tailored to site-specific geomechanical conditions and operational demands.

Recent advancements in artificial intelligence (AI) and neural networks have opened new horizons for predictive management and optimization of mine support systems (**Psyuk & Polyanska, 2024**). These technologies offer the capability to process and interpret large volumes of data collected from sensors embedded throughout the underground mine environment (**Rastsvietaiev et al., 2015; Blinov et al., 2025**). By continuously monitoring parameters such as stress levels, displacement, vibration, and load distribution, AI-driven models can provide real-time assessments of support integrity and detect early signs of potential failure (**Psyuk & Polyanska, 2024; Chen & Chen, 2024**). Neural networks are highly effective in simulating complex, nonlinear interactions between suspended monorail loads, structural support elements, and the surrounding rock mass under dynamic operating conditions (**Psyuk & Polyanska, 2024; Zapukhliak et al., 2019**). These models enable the identification of hidden patterns and relationships that traditional analytical methods may overlook. As a result, intelligent systems can facilitate the dynamic adjustment of fastening parameters, such as anchor length, spacing, and installation angles, based on changing geomechanical and operational conditions (**Sosnowski et al, 2024**). The integration of AI into mine supports design and monitoring significantly enhances operational reliability, safety, and the overall efficiency of transportation systems in deep and structurally complex mining environments (**Rastsvietaiev et al., 2015; Kononenko & Khomenko, 2010; Zapukhliak et al., 2019; Sosnowski, Dyczko & Kamiński, 2024; Polyanska et al., 2024**).

Sustainable mining practices increasingly demand that support and transportation systems are designed not only for operational efficiency but also for minimal environmental impact (**Khomenko et al., 2018; Lewicka & Lewicka, 2019; Bashynska et al., 2024**). Frame-anchor fastening systems must be evaluated in terms of both their mechanical performance and their influence on the surrounding geological and hydrogeological environment (**De Borst et al., 2012**; **Myronova et al., 2025**). Improperly designed or overloaded support systems can result in excessive deformation, leading to ground subsidence, fracture propagation, or contamination of groundwater resources (**Moldabayev et al., 2021; Kononenko et al., 2023**). Such consequences pose significant environmental risks and may compromise the long-term stability of the mine and its surrounding ecosystem (**Lewicka & Lewicka, 2019**; **Lapshyn et al., 2025**). To address these challenges, recent research has focused on integrating environmental monitoring with structural management strategies, including the use of predictive modelling and geotechnical feedback systems (**Lewicka & Lewicka, 2019**; **Kononenko et al., 2023; Lapshyn et al., 2025; Fedoreiko et al., 2025**). This holistic approach helps to balance the goals of resource extraction with the need for environmental protection, thereby contributing to the long-term sustainability and regulatory compliance of mining operations.

Innovations in fastening materials, including high-strength alloys, fiber-reinforced composites, and corrosion-resistant coatings, have been extensively investigated to enhance the durability and load-bearing capacity of frame-anchor systems in mining environments (**Lewicka & Lewicka, 2019**; **Kumbasaroglu, 2010, Symanovych et al., 2015**). These advanced materials are designed to withstand the harsh conditions of underground operations, including exposure to moisture, aggressive geochemistry, and fluctuating mechanical loads (**Kononenko et al., 2023; Kononenko et al., 2016; Kumbasaroglu, 2010; Stöcklein & Kaliske, 2022**). In parallel, research has focused on improving installation techniques, such as deep embedding, prestressed anchoring, and chemical grouting, to increase the overall quality and reliability of anchorage, particularly under dynamic loading conditions generated by suspended monorail transport (**Herasymenko et al., 2023; Rastsvietaiev et al., 2015; Kononenko & Khomenko, 2010; Beshta et al., 2015**). The performance of these materials and installation methods under cyclical and impact loading is a key area of study, as it directly informs the development of technical standards and guidelines for the selection and application of fastening systems in preparatory mine workings (**Kumbasaroglu, 2010; Symanovych et al., 2015; Jiang et al., 2025**). Ultimately, the integration of advanced materials with optimized installation practices contributes to safer, more efficient, and longer-lasting support structures in modern underground mining operations.

Numerical methods and finite element modelling play a crucial role in understanding the stress-strain behaviour of combined frame-anchor support under dynamic conditions. Simulation tools allow researchers to vary design parameters systematically and predict their impact on system stability and deformation patterns (**Stöcklein & Kaliske, 2022; Sobolev et al., 2025**). This approach supports the design of fastening schemes that optimize load transfer and minimize risks of failure, facilitating evidence-based decision-making in mine management (**Vladyko et al., 2025; Zhai et al., 2025**). Despite progress, challenges remain in fully characterizing the complex interactions in the "suspended monorail – mine support – rock mass" system, especially under varied geological conditions and intensified operational loads. Issues such as real-time monitoring under harsh underground environments, integration of AI models with existing mine management systems, and scaling laboratory findings to field applications require ongoing research (**Kosenko et al., 2025; Psyuk & Polyanska, 2024**, **Zapukhliak et al., 2019**; **Campos Zabala, 2023**). Addressing these gaps is essential for developing robust fastening solutions adaptable to evolving mining demands.

The current body of literature indicates a clear need for comprehensive studies that combine experimental field data, predictive modelling, and advanced computational simulations to refine frame-anchor fastening parameters specifically for monorail-based heavy cargo transportation. The purpose of this research is to develop innovative technological schemes and establish optimal fastening configurations that ensure safe, efficient, and environmentally sustainable transportation in complex underground mining conditions. This work aims to contribute to improved management practices by integrating multidisciplinary approaches for enhanced operational resilience.

2. Methods

The methodology of this study is based on an integrated approach combining numerical modelling, structural simulation, and field data analysis to determine optimal parameters for frame-anchor fastening systems in preparatory mine workings used for monorail-based heavy cargo transportation (**Herasymenko et al., 2023; Rastsvietaiev et al., 2015; Babets et al., 2023; Carrascal et al., 2007**). The study begins with the development of a conceptual model of the transport-technological system "suspended monorail – frame-anchor support – rock mass," taking into account the dynamic interaction between these components under operational conditions. Using SolidWorks Simulation software, finite element analysis (FEA) was conducted to evaluate the stress-strain behaviour of various support configurations under dynamic loading generated by moving large-tonnage cargo (**Rastsvietaiev et al., 2015; Babets et al., 2023; Carrascal et al., 2007; Zapukhliak et al., 2019; Sala & Bieda, 2024**). Key parameters, such as anchor length, spacing, depth of anchorage, and arch frame pitch, were systematically varied to assess their influence on support stability and rock mass deformation (**Babets et al., 2023**, **Tereshchuk et al., 2018; Bondarenko et al., 2021; Ko-**

valevska et al., 2020). Dynamic loads from train movement and emergency braking scenarios were simulated to reflect realistic mine conditions.

Field observations were conducted in an active underground coal mine where suspended monorail transport is routinely used for the delivery of mechanized support components. Instrumentation, including displacement sensors and vibration monitors, was installed along selected sections of district workings to record real-time deformation and load responses during monorail operation. Laboratory testing of fastening elements, including high-strength anchors and steel arch frames, was also carried out to determine material behaviour under cyclic and impact loading (**Herasymenko et al., 2023; Rastsvietaiev et al., 2015; Yegorchenko et al., 2022; Bashynska, 2025**). The combination of numerical modelling, field monitoring, and lab-based mechanical testing enabled a comprehensive validation of simulation results and informed the development of rational design parameters. This methodology ensures the reliability, safety, and performance of the support system under dynamic operational loads.

As it had been mentioned to determine rational schemes of frame-anchor support for preparatory mine workings that ensure the safe transportation of large-tonnage cargo via suspended monorail systems, a comprehensive research methodology was developed. The methodology focused on analyzing the stress–strain state of components within the transport-technological system "suspended monorail – mine support – rock mass" using numerical modelling in the SolidWorks Simulation environment (**Yegorchenko et al., 2022**). The modelling aimed to simulate and assess the behaviour of support structures under dynamic loading conditions typical of underground mining operations.

At the initial stage, parametric 3D models of the frame-anchor support system were constructed. These included various configurations of steel arch frames and anchors of differing lengths and anchoring types (**Khomenko et al., 2018**). The geometrical and mechanical parameters of the models reflected typical dimensions of preparatory mine workings and the mining-geological conditions of sites where suspended monorail transport is operationally implemented (**De Borst et al., 2012; Ravichandran, 2020**). The rock mass was modelled as a solid continuum with variable mechanical properties to reflect realistic stratified and fractured media.

To analyze the stress–strain state (SSS) of the support structure under dynamic loading conditions, the Static Study module of SolidWorks Simulation was utilized, applying the finite element method (FEM) (**Zienkiewicz et al., 2013; Lewicka & Zakrzewska-Bielawska, 2019**). This computational approach allowed for accurate modelling of the mechanical response of the combined frame-anchor support system under realistic operational stresses generated by monorail-based heavy cargo transport. The simulation aimed to evaluate structural stability, deformation behaviour, and stress distribution in both the support elements and the surrounding rock mass (**Moldabayev et al., 2021; Sun et al., 2009**).

The numerical analysis considered several key input conditions. Material properties were defined based on standard specifications: steel (according to DST 27772-2015 or DIN EN 10025) was used for the arch frame elements, while the rock mass was modelled as a conditionally fractured medium with variable strength parameters, including elastic modulus and Poisson's ratio (**DST 27772-2015. Rolled steel for construction purposes; DIN EN 10025-1:2019. Hot rolled products of structural steels**). Boundary conditions involved fixing the periphery of the model to simulate confinement by the surrounding geological environment and applying external loads that represented both mining pressure and dynamic impulses from moving monorail vehicles (**Moldabayev et al., 2021; Lewicka & Zakrzewska-Bielawska, 2019; Vosoughifar, Madadi & Rabiefar, 2017**).

Contact conditions were defined to reflect realistic interactions between system components, either frictional or adhesive, depending on the type of anchor-rock and frame-rock connections being modelled (**Sakurai, 2010**). As a result of the numerical modelling, distributions of stress, displacement, and safety factors were obtained for various frame-anchor support schemes. Special attention was given to three key indicators:

- Maximum stresses that may induce strength loss or plastic deformation;
- Displacements and deflections of frame elements, particularly at monorail load application points;
- Zones of stress concentration in anchor elements, indicating areas at high risk of rock failure or slippage.

Further simulations involved a series of parametric studies to optimize frame spacing, anchor length, and anchorage depth. Various anchor geometries and placement schemes were evaluated to determine their effect on the overall load distribution and support system performance. Model identification (**Kononenko et al., 2024**) was carried out by solving boundary value problems for fractured rock masses using a linear anisotropic constitutive model. A key aspect of this identification involved reproducing the principal tensile and compressive stress fields that develop around load-bearing arches under dynamic monorail loading. These stresses were then used to define loading parameters for secondary anchor levels.

The geometric dimensions of the model were determined using the following dynamic loads:

$$B = h + 4D_{eq}, \text{ m} \qquad (1)$$

Where:

h – height of the mine working [m],

D_{eq} – equivalent diameter of the mine working [m], calculated as:

$$D_{eq} = \sqrt{4\frac{S_c}{\pi}}, \text{m} \quad (2)$$

Where S_c is the cross-sectional area of the working [m²].

This approach makes it possible to accurately determine the characteristic geometric parameters of the excavation for further numerical modelling under dynamic loading conditions. Such precision is essential for correctly reproducing the stress–strain state of the rock mass and its interaction with the support elements. As a result, the developed model provides a reliable foundation for assessing the stability and safety of the entire "suspended monorail – mine support – rock mass" system.

The required length of the second-level anchors was computed as:

$$l_{anchor} = l_I + l_{emb} + l_{lock}, \text{m} \quad (3)$$

Where:

- l_I – design length of first-level roof anchors,
- l_{emb} – embedding depth of the suspension anchors above the first-level anchors (≥ 0.5 m for roof type II; ≥ 1.0 m for types I, III, IV),
- l_{lock} – locking section length.

Initial loads and boundary constraints were applied in the simulation, along with finite element meshing. The maximum load on the "monorail support – mine support" subsystem was calculated according to **Herasymenko et al. (2023)** using the following equation:

$$P = \frac{P_s^{max} k_d}{b C_s}, \text{kN} \quad (4)$$

Where:

- P_s^{max} – maximum static load on one monorail suspension [kN],
- C_s – distance between suspensions [m],
- k_d – dynamic load coefficient.
- b – correction factor related to the width of the monorail support structure.

The simulation results were validated through comparison with data obtained from technical documentation and in-situ observations of support system behaviour under similar mining conditions. This validation step was essential for verifying the accuracy of the computational model and ensuring that it adequately represented the real-world performance of the frame-anchor support system. Based on the observed deviations and structural responses, necessary adjustments were made to the model parameters, which enhanced their reliability and applicability for conducting further variant calculations and scenario-based analyses.

Given the complexity of the overall transport-technological system, the interaction between the suspended monorail, the mine support, and the surrounding rock mass was examined by splitting the system into three interrelated subsystems: (1) "rolling stock – monorail support," (2) "monorail support – mine support," and (3) "mine support – rock mass." This modular approach allowed for a more focused and systematic analysis of individual stress transfer mechanisms at each interface. By isolating the influence of dynamic loads at each subsystem level, it became possible to identify structural vulnerabilities and develop targeted improvements in fastening design, particularly in areas prone to deformation, stress concentration, or progressive failure under cyclic monorail loading

3. Results

According to the research program and methodology developed for analyzing the interaction mechanisms within the "suspended monorail – mine support – rock mass" system, each of the designated subsystems was examined step by step as an independent structural entity. This modular approach allowed for a clearer understanding of load transfer processes and the localized effects of dynamic forces at each interaction level. In particular, the current article presents the results of a detailed study focused on the stress–strain state of components within the "Monorail Support – Mine Support" subsystem. The analysis emphasizes how dynamic loading, induced by monorail movement and braking, affects the mechanical performance and deformation behaviour of the fastening structures. The findings contribute to optimizing the frame-anchor support configuration and improving the structural reliability of preparatory mine workings under operational transport conditions.

According to the developed methodology, for modelling the interaction conditions within the "monorail support – mine support" subsystem using SolidWorks Simulation consists of several key stages. These include model identification, the creation of input data for geometric modelling, and the assignment of material properties for all structural components. Load parameters, boundary constraints, and finite element meshing are then defined to simulate operational conditions. Finally, the results are analyzed with particular attention to dynamic loads on anchors, focusing on stress variations around the crowns of load-bearing arches.

The obtained interaction parameters of elements within the "monorail support – mine support" subsystem served as the basis for developing a database to simulate changes in their technical condition under dynamic loads. This database enabled the formulation of innovative engineering solutions aimed at mitigating adverse effects on arch crowns and the mine roof. Operational studies of suspended monorail systems under atypical and extreme mining conditions (**Rastsvietaiev et al., 2015**) revealed that, to reduce the negative influence of rolling stock on both arch supports and the surrounding rock mass, dynamic loads must be evenly redistributed via the monorail support structure across all interacting components. To achieve this, the integration of deep-embedded anchors into existing frame-anchor fastening schemes is recommended, allowing the monorail support to be fixed directly to these anchors. This configuration effectively transfers part of the dynamic loading from the rolling stock onto the load-bearing arches and secondary anchorage points, thereby enhancing system stability.

The methodology for assessing dynamic loads acting on second-level anchors involves modelling the development of the stress–strain state of anchor elements under extreme operational conditions. According to engineering guidelines (**Aitkazinova et al., 2022**), this process includes several stages. Initially, a dataset is compiled to determine the technical condition of second-level anchors. This dataset includes the spatial orientation of anchors within the working, their physical and mechanical properties in situ, and environmental factors adversely affecting their performance. Such factors include vibration intensity, cyclic loading, and shock impulses, which deteriorate the structural integrity of mine support systems over time.

The primary sources of data include design specifications, construction and maintenance documentation (**Bondarenko et al., 2021**), as well as the results of dedicated investigations focused on dynamic load effects (**Zienkiewicz et al., 2013**) on subsystem elements during large-tonnage cargo transportation. Following the approved research methodology, a comprehensive stress–strain analysis of the subsystem components was performed. Critical zones with the highest stress concentrations were identified, and their actual load-bearing capacity was assessed to verify compliance with normative safety standards. Experimental observations confirmed that recurring dynamic loads, especially those generated as rolling stock pass over deformed joints in the monorail track, contribute to wear, fatigue, and damage in the supports of preparatory workings.

Building on the developed simulation methodology (**Moldabayev et al., 2021**) for evaluating suspended monorail operating regimes, data from experimental studies were incorporated into models simulating the behaviour of deep-embedded anchors under dynamic conditions during large-tonnage transport. In the modelling process, the second-level anchors and mine working were jointly analyzed as an integrated system within SolidWorks Simulation. Utilizing the finite element method (FEM) (**Khomenko et al., 2023**), structural analysis of system performance under dynamic loads was conducted, allowing predictions of anchor behaviour under realistic mining conditions. The objective of this methodology was to determine the maximum permissible stress levels in the anchor support elements using parametric CAD-based models (**Tereshchuk et al., 2018; Otey et al., 2018**), thereby ensuring both safety and operational reliability in transport-intensive underground environments.

The modelled mine section incorporated second-level anchors with a length of 3.4 meters, specifically designed to support suspended diesel locomotives (SDLs). These anchors are fabricated from high-strength wire rope steel and do not include additional protective coatings or corrosion-resistant treatments. The selection of material reflects typical in-mine operating conditions and mechanical loading scenarios associated with monorail transport. The physical and mechanical properties assigned to these elements in the CAD-based finite element models are summarized in **Table 1**.

Table 1. Main properties of wire rope steel

Property	Value	Unit
Elastic modulus	190000	N/mm²
Shear modulus	75000	N/mm²
Density	8000	kg/m³
Tensile strength limit	517	N/mm²
Poisson's ratio	0.29	
Yield strength	206	N/mm²
Thermal conductivity	16	W/(m·K)
Specific heat	500	J/(kg·K)

Table 2. Geometric dimensions of the model for simulation

Property	Value	Unit
Model height, B	24	m
Depth of occurrence, H	300	m
Average rock density, γ	2600	kg/m³
Poisson's ratio μ	0.25	
Mine working width, b	4460	mm
Mine working height, h	3800	mm
Inclination angle of second-level anchors, β	70	degrees
The length of second-level anchors, l_{anchor}	3400	mm

To simulate the interaction conditions of the elements within the technical subsystem "monorail support – mine support" in a CAD environment, a reference section was selected from an existing preparatory working at the Stepova mine operated by DTEK Pavlohradvuhillia, based on its current operational conditions. The selection of this site provided realistic boundary and loading conditions for accurate numerical modelling.

Based on the results of the mathematical simulation of subsystem behaviour, the model dimensions were determined while ensuring that the influence of external geometry on the simulation results was minimized. The model geometry was constructed at a 1:1 scale (**Kovalevska et al., 2020**), in accordance with the specifications provided in **Table 2**.

To determine the geometric dimensions of the model, a set of analytical expressions was used, including **Equation 1** for calculating the overall width of the modelled domain. The equivalent diameter of the mine working was obtained using **Equation 2**, which accounts for

Table 3. Physical and mechanical properties of rocks

	Elastic modulus, N/mm²	Poisson's ratio	Tensile strength limit, N/m²	Compressive strength, N/m²	Humidity, %	Fracturing
Siltstone	16600	0,394	18	381	2.0	1-3
Argillite	21200	0,41	25	280	2.6	4-5
Sandstone	27100	0,41	150	680	5.2	1-3
Coal	4700	0,33	14	300	4.4	10-15

the cross-sectional area of the excavation. These expressions ensured that the model reflected the actual geometry of the underground environment with sufficient accuracy for finite element simulation. In addition, the length of the second-level anchors was calculated using **Equation 3**, which considers the combined depth of primary anchorage, the embedding section, and the locking zone. These parameters were critical for replicating the interaction between the support system and the surrounding rock mass under dynamic loading conditions. Together, the applied equations formed the basis for building a physically representative CAD model suitable for stress-strain analysis using numerical methods.

The initial material properties used in the numerical model were defined based on the physical and mechanical characteristics of rock types commonly encountered in the mines of the Western Donbas region (**Khomenko et al., 2018**). These properties include parameters such as density, compressive strength, Young's modulus, and Poisson's ratio, which are essential for simulating the stress–strain behaviour of the rock mass under load. The selected values reflect average conditions derived from geological surveys and laboratory testing of core samples collected from operating mine sites. **Table 3** presents a summary of these average material properties, which were used as input for the finite element analysis. These values were further verified and calibrated to ensure compatibility with the dynamic loading conditions associated with suspended monorail operations. Incorporating realistic geomechanical data into the model was crucial for obtaining accurate simulation results and reliable safety assessments of the support system.

In practice, monorail support is suspended to the crowns of metal arch supports or to anchors. The proposed combined suspension system is simultaneously fixed to the crowns of the arch support and to deep-embedded anchors using chains. Suspension segments are interconnected in a way that ensures even distribution of dynamic loads from the transportation of heavy cargo between both types of support. This engineering solution allows each type of support to be considered individually, taking into account the nature of dynamic load transfer, which improves the reliability of the entire support system of the mine roadway.

The next stage of the modelling process involved defining the initial load P, applying boundary constraints, and generating the finite element mesh to discretize the model geometry. According to the recommendations presented in **Herasymenko et al. (2023)**, the load acting on the subsystem element "monorail support – mine support" is calculated using **Equation 4**. This equation accounts for the maximum static load on individual suspensions, the spacing between suspensions, and a dynamic load coefficient that reflects operational conditions. Proper implementation of these parameters is critical to accurately simulate dynamic interactions within the system and assess the resulting stress distribution.

According to the assessment of the technical condition of suspended monorail track support systems, the most deformation-prone areas are located at the junction between the crown of the arch support and the attachment points of the second-level anchors. Theoretical studies of the interaction conditions between the elements of the technical subsystem "monorail support – mine support" during the transportation of heavy loads have shown that the monorail track is divided into characteristic zones with the highest levels of dynamic loading (see **Figure 1**). To calculate the load and deformation in the characteristic nodes of the elements of the technical subsystem "monorail - fastening of the workings", the deep-seated anchor zones were divided into element-by-element grids using the FEM (**Kononenko et al., 2023**).

The application of SolidWorks Simulation software for modelling the technical condition of the monorail track enabled the determination of equivalent stresses and the tensile strength limits of second-level anchors during large-tonnage cargo transport. According to manufacturer specifications, the permissible tensile strength of the second-level anchors is 240 MPa. Simulation results were obtained for two different spatial arrangements of deep-embedded anchors, incorporating the dynamic load coefficient and assuming uniform load distribution among the frame-anchor support elements. The key findings of these analyses are summarized in **Table 4**.

Figure 2 illustrates the distribution of von Mises stresses generated in the deep-embedded anchors due to dynamic loads from the transportation of large-tonnage cargo weighing 8, 12, and 16 tons. These stress values reflect the complex interaction between the moving load and the support elements under realistic operational conditions. The calculated von Mises stress intensities, expressed in megapascals (MPa), serve as critical indicators for evaluating the structural integrity and safety margins of the anchors. By comparing these stress levels with the permissible tensile strength of the anchor material, it is possible to assess the reliability and durability of the fas-

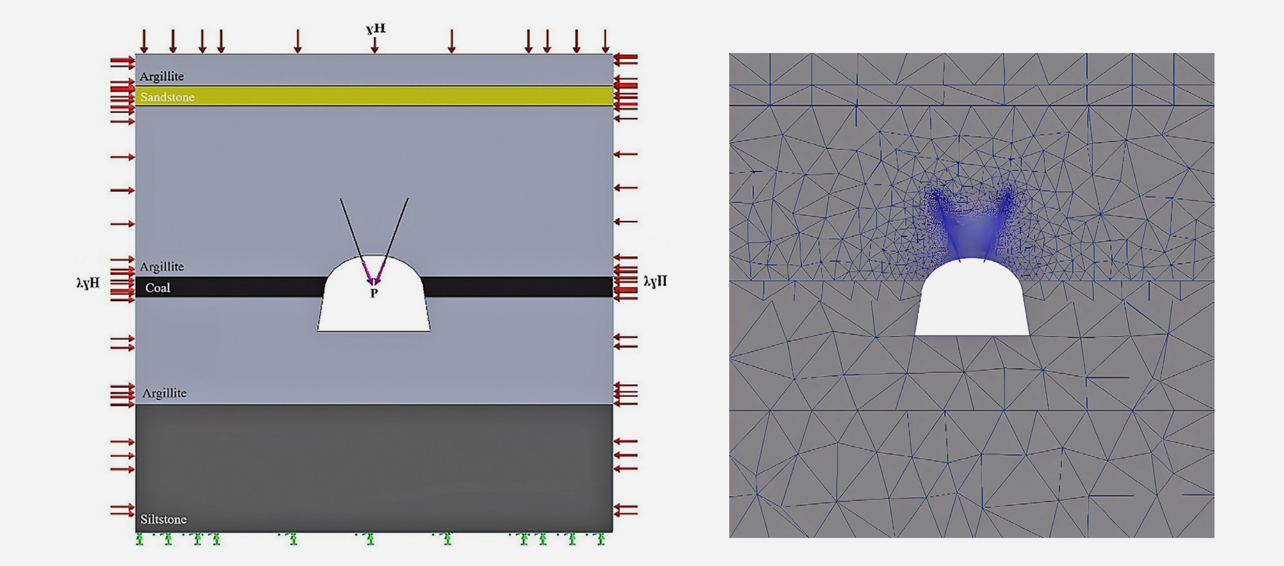
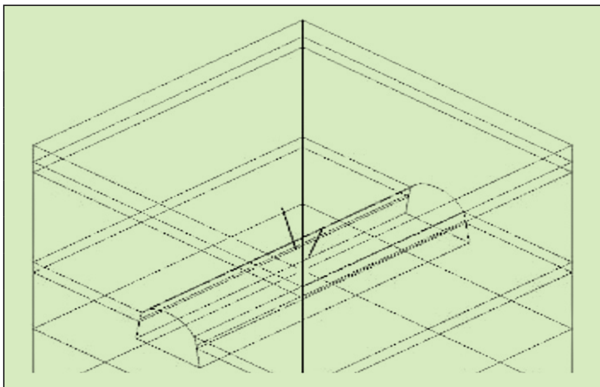


Figure 1. Initial constraints, applied loads, and finite element mesh of the model

Table 4. Simulation results for stress in deep-embedded anchors under dynamic loading



Cargo mass (tons)	Von Mises stress σ_{von} Mises (MPa)
2	63
4	95
6	127
8	159
10	190
12	222
14	255
16	287

tening system. This analysis provides essential data to guide the design and optimization of anchor placement to ensure safe and efficient mine transport operations.

The developed software package allows us to establish (see **Figure 2**) the possibility of safe transportation of high-tonnage cargo weighing up to 12 tons without destroying the structure of the proposed fastening system. The conducted simulations confirm the reliability of the system under various loading and dynamic impact conditions. This provides a solid basis for further optimization of the design parameters and practical implementation of the technology in real mining environments.

After approximating the maximum values shown in **Figure 3**, an empirical relationship was established describing how the von Mises stress intensity $\sigma_{von\ Mises}$ in the second-level anchor varies with the mass of the large-tonnage load *P* This dependence provides a quantitative basis for predicting stress responses in the anchor under different cargo weights. The derived formula enables engineers to estimate stress levels for various operational scenarios, facilitating risk assessment and design optimization. Such insights are critical for ensuring the structural integrity and safe performance of the anchoring system in mining transport applications.

For the anchors of the second level, the magnitude of the von Mises stresses depending on the mass of the large-tonnage load is determined by the equation:

$$\sigma_{\text{von Mises}} = 21P - 0{,}19P^2 \text{ MPa},$$
$$\text{attached to } R^2 = 0{,}9987 \qquad (5)$$

Where *P* – cargo mass, tons; R^2 – reliability of approximation.

The second level anchor strength check is performed under the following conditions

$$\sigma_{\text{von Mises}} < [\sigma_y] \text{ MPa} \qquad (6)$$

Where σ_y – yield strength of anchor material, MPa.

According to theoretical studies, the destruction of the anchor fastening will occur when the load weight

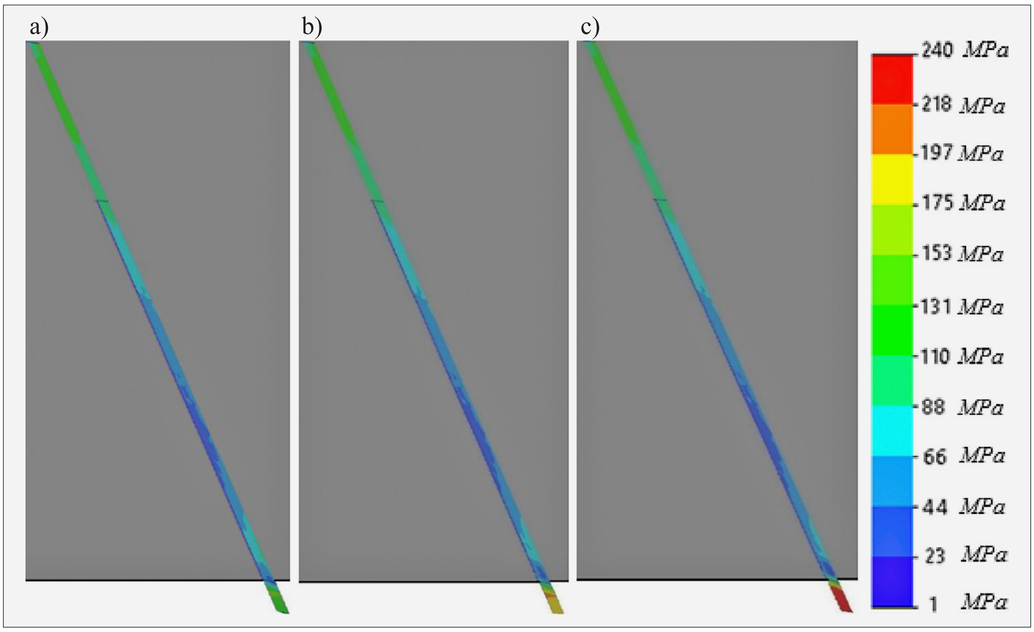


Figure 2. Von Mises stress intensities in deep-embedded anchors depending on cargo mass: a – 8 t; b – 12 t; c – 16 t

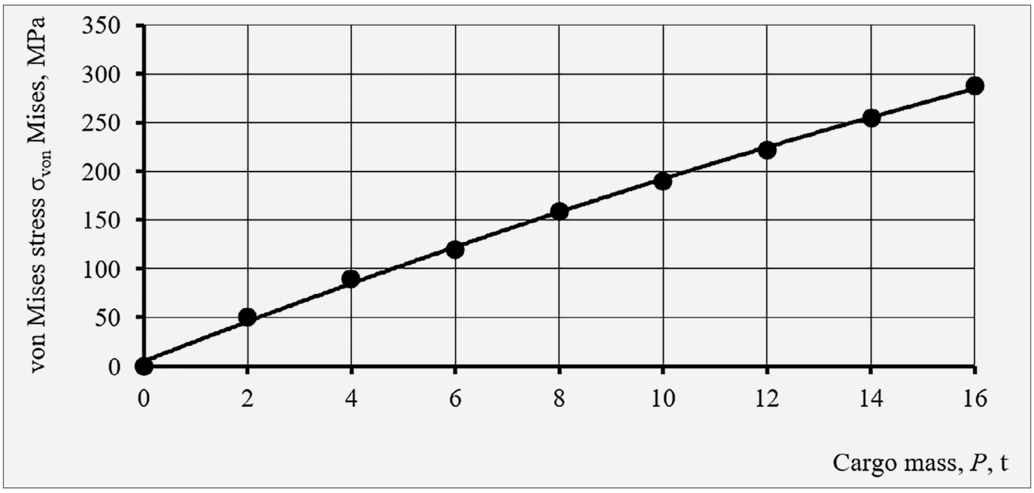


Figure 3. Graph of von Mises stress intensity in a second-level anchor versus cargo mass *P*

reaches 13 tons or more. This critical value determines the upper safety limit for the proposed fastening system under operational conditions. Exceeding this threshold may lead to structural deformation and a loss of load-bearing capacity. Therefore, it is recommended to maintain the operating load within the safe range identified to ensure long-term system reliability and stability.

4. Discussion

The predicted relationship between the von Mises stress intensity $\sigma_{von\ Mises}$ in deep-embedded anchors and the mass *P* of large-tonnage cargo is presented in **Table 5**. This data provides a clear overview of how increasing load mass affects the stress distribution within the anchoring system. Such predictions are essential for assessing the safety margins and optimizing the design of mine support structures under varying operational conditions.

The analysis of the simulation results for the interaction conditions within the "monorail support – mine support" subsystem demonstrates that employing a combined frame-anchor fastening, where the monorail support is simultaneously secured to second-level anchors and the crowns of arch supports, can significantly enhance system performance. Under the specific operational conditions of the Western Donbas mining region, this fastening approach facilitates the expansion of potential reserves for diesel suspension monorail roads. This method improves the stability and load-bearing capacity of the support system, thereby increasing the efficiency and safety of underground transport infrastructure.

Table 5. Prediction of the dependence of the stress intensity against the $\sigma_{von\ Mises}$ background of deep-seated anchors on the mass *P* of a large-tonnage cargo.

Cargo mass (tons)	Von Mises stress σ_{von} Mises (MPa)
1	39
2	63
3	81
4	95
5	111
6	127
7	143
8	159
9	175
10	190
11	206
12	222
13	239
14	255
15	270
16	281

The interaction indicators obtained through computer modelling of the “monorail support – mine support” subsystem demonstrate that dynamic loads can be significantly mitigated by effectively redistributing the mass of large-tonnage cargo across multiple elements within the complex dynamic transport-technological system “suspended monorail – mine support – rock mass.” The implemented innovative technical solutions have raised the maximum permissible operational thresholds for suspended monorail tracks transporting heavy loads, thereby enhancing overall system reliability. This advancement also expands the potential for broader application of suspended monorail systems under the challenging geological and operational conditions characteristic of the Western Donbas region.

5. Conclusions

This research successfully employed a modular approach to analyze the interaction mechanisms within the “suspended monorail – mine support – rock mass” system, focusing specifically on the “monorail support – mine support” subsystem. The use of finite element modelling through SolidWorks Simulation enabled a comprehensive evaluation of the stress–strain states under dynamic loads typical for large-tonnage cargo transport. The study identified critical stress concentration zones, particularly at the junctions of anchors and arch crowns, providing valuable insight to optimize frame-anchor fastening designs and thereby enhance the structural reliability and operational safety of preparatory mine workings.

Numerical simulations demonstrated that integrating deep-embedded second-level anchors into combined frame-anchor fastening schemes effectively redistributes dynamic loads from the suspended monorail rolling stock across multiple support elements. This redistribution leads to a significant reduction in peak stress and deformation risks in vulnerable zones of the support system. Furthermore, the establishment of empirical relationships between cargo mass and von Mises stress in anchors allows for precise prediction of stress responses, ensuring that operational loads remain within permissible strength limits. These findings support the development of more resilient support systems capable of withstanding the challenging mining conditions prevalent in the Western Donbas region.

The simulation results also revealed that the tensile strength limit of second-level anchors, specified at 240 MPa, is reached when transporting cargo exceedingly approximately 13 tons. This threshold defines the upper safe operational boundary for suspended monorail transport under current design parameters. The combined fastening scheme, whereby the monorail support is anchored simultaneously to second-level anchors and arch crowns, facilitates a more uniform distribution of dynamic loads and reduces stress intensities in critical structural zones, thereby extending the service life and safety of the support system.

The practical recommendations derived from this research can be directly applied to the design and modernization of preparatory mine workings equipped with suspended monorail transport systems. The proposed innovative fastening solutions improve mining efficiency by accelerating panel preparation, minimizing maintenance and repair costs, and enhancing overall system reliability. Moreover, these solutions are highly adaptable for implementation in mines of Western Donbas as well as other mining regions with comparable geomechanical and operational conditions.

In conclusion, the developed technical framework provides a robust engineering basis for increasing the maximum allowable operational thresholds of suspended monorail tracks transporting heavy loads. By improving load management and reinforcing system stability, the study contributes to safer and more efficient underground transport infrastructures. These advancements also lay the groundwork for future development, standardization, and broader adoption of suspended monorail transport technologies in the global mining industry.

Further research is planned to be devoted to the unification of all subsystems into a single complex system “suspended monorail – mine support – rock mass” and the analysis of its operation. This approach will make it possible to comprehensively evaluate the mutual influence of mechanical, structural, and geological components. The obtained results are expected to form the basis for optimizing design parameters and improving the overall stability and efficiency of the system.

6. References

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

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. Ethical aspects of AI use in the circular economy. AI & Society (2025). https://doi.org/10.1007/s00146-025-02436-1

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

Beshta, O., Albu, A., Balakhontsev, A., & Fedoreyko, V. (2015). Universal model of the galvanic battery as a tool for calculations of electric vehicles. *Power Engineering, Control and Information Technologies in Geotechnical Systems*, 7–11. https://doi.org/10.1201/b18475-2

Blinov, I., Radziukynas, V., Shymaniuk, P., Dyczko, A., Stecuła, K., Sychova, V., Miroshnyk, V., & Dychkovskyi, R. (2025). Smart Management of Energy Losses in Distribution Networks Using Deep Neural Networks. *Energies*, 18(12), 3156. https://doi.org/10.3390/en18123156

Bondarenko, V., Kovalevska, I., Cawood, F., Husiev, O., Snihur, V., et al. (2021). Development and testing of an algorithm for calculating the load on support of mine workings. *Mining of Mineral Deposits, 15*(1), 1–10. https://doi.org/10.33271/mining15.01.001

Campos Zabala, F. J. (2023). Integrating AI into Existing Systems and Processes. *Grow Your Business with AI*, 413–431. https://doi.org/10.1007/978-1-4842-9669-1_18

Carrascal, I. A., Casado, J. A., Polanco, J. A., & Gutiérrez-Solana, F. (2007). Dynamic behaviour of railway fastening setting pads. *Engineering Failure Analysis*, 14(2), 364–373. https://doi.org/10.1016/j.engfailanal.2006.02.003

Chen, Z., & Chen, Y. (2024). Advancing AI-Driven BETC Models for Transformative Educational Data Mining and Learning Analytics. Proceedings of the 2024 International Symposium on Artificial Intelligence for Education, 495–500. https://doi.org/10.1145/3700297.3700382

De Borst, R., Crisfield, M. A., Remmers, J. J. C., & Verhoosel, C. V. (2012). *Nonlinear finite element analysis of solids and structures*. John Wiley & Sons, 544 p.

DIN EN 10025-1:2019. Hot rolled products of structural steels – Technical delivery conditions.

DST 27772-2015. Rolled steel for construction purposes. Technical conditions.

Dychkovskyi, R., Dyczko, A., & Borojević Šoštarić, S. (2024). Foreword: Physical and Chemical Geotechnologies – Innovations in Mining and Energy. *E3S Web of Conferences*, 567, 00001. https://doi.org/10.1051/e3sconf/202456700001

Dychkovskyi, R., Saik, P., Sala, D., & Cabana, E. C. (2024). The current state of the non-ore mineral deposits mining in the concept of the Ukraine reconstruction in the post-war period. *Mineral Economics*, 37(3), 589–599. https://doi.org/10.1007/s13563-024-00436-z

Falshtynskyi, V., Dychkovskyi, R., Khomenko, O., & Kononenko, M. (2020). On the formation of a mine-based energy resource complex. *E3S Web of Conferences*, 201, 01020. https://doi.org/10.1051/e3sconf/202020101020

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

Herasymenko, A. O., Rastsvietaiev, V. O., & Shyrin, A. L. (2023). Selection of the means of auxiliary transportation facilities and adaptation of their parameters to specific operation conditions. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (2), 40–46. https://doi.org/10.33271/nvngu/2023-2/040

Jiang, Y., Duan, P., Liu, W., Du, Z., & Chen, R. (2025). Dynamic performance analysis of suspended monorail vehicles under various operating conditions. *International Journal of Vehicle Systems Modelling and Testing*, 1(1). https://doi.org/10.1504/ijvsmt.2025.10071184

Kang, H., Yang, J., Gao, F., & Li, J. (2020). Experimental Study on the Mechanical Behavior of Rock Bolts Subjected to Complex Static and Dynamic Loads. *Rock Mechanics and Rock Engineering,* 53(11), 4993–5004. https://doi.org/10.1007/s00603-020-02205-0

Khomenko, O., Kononenko, M., & Bilegsaikhan, J. (2018). Classification of theories about rock pressure. *Solid State Phenomena*, 277, 157–167. https://doi.org/10.4028/www.scientific.net/ssp.277.157

Khomenko, O., Kononenko, M., Kovalenko, I., & Astafiev, D. (2018). Self-regulating roof-bolting with the rock pressure energy use. *E3S Web of Conferences, 60*, 00009. https://doi.org/10.1051/e3sconf/20186000009

Khomenko, O., Rudakov, D., Lkhagva, T., Sala, D., Buketov, V., & Dychkovskyi, R. (2023). Managing the Horizon-oriented In-Situ Leaching for the Uranium Deposits of Mongolia. *Rudarsko-Geološko-Naftni Zbornik*, 38(5), 49–60. https://doi.org/10.17794/rgn.2023.5.5

Kononenko, M., & Khomenko, O. (2010). Technology of support of workings near to extraction chambers. In *New Techniques and Technologies in Mining,* 193–197. https://doi.org/10.1201/b11329-32

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

Kononenko, M., Khomenko, O., Kovalenko, I., Kosenko, A., Zahorodnii, R., & Dychkovskyi, R. (2023). 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. (2023). 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., Sudakov, A., Drobot, S., & Lkhagva, T. (2016). Numerical modelling of massif zonal structuring around underground working. *Mining of Mineral Deposits*, 10(3), 101–106. https://doi.org/10.15407/mining10.03.101

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

Kovalevska, I., Symanovych, H., Jarosz, J., Barabash, M., & Husiev, O. (2020). Geomechanics of overworked mine working support resistance in the laminal massif of soft rocks. *E3S Web of Conferences, 201*, 01003. https://doi.org/10.1051/e3sconf/202020101003

Kumbasaroglu, A. (2010). An experimental study on the effects of anchor rods on infill walled frame systems. *Erzincan Binali Yildirim University*, 211. https://doi.org/10.71008/atauni.thesis.2010.101

Lapshyn. Y., Shevchenko. O., Dybrin S., & Dychkovskyi. R. (2025). Feasibility of Fine Classification in Processing Watered Coal Sludge from Storage: A Case Study of the Dnipro Coke Chemical Plant. *Acta Montanistica Slovaca*, 100. https://doi.org/10.46544/ams.v30i1.07

Lewicka, B., & Lewicka, D. (2019). Environmental risk management in the context of environmental management systems for agriculture based on the ISO 14001:2015 standard. *Acta Innovations*, 33, 63–72. https://doi.org/10.32933/actainnovations.33.6 V

Lewicka, D., & Zakrzewska-Bielawska, A. (2019). Interorganizational Trust in Business Relations: Cooperation and Coopetition. *Contemporary Challenges in Cooperation and Coopetition in the Age of Industry 4.0*, 155–174. https://doi.org/10.1007/978-3-030-30549-9_8

Mackiewicz, M., Krentowski, J. R., Knyziak, P., & Wardach, M. (2022). Consequences of excessive deformation of structural elements in precast buildings. *Engineering Failure Analysis*, 137, 106261. https://doi.org/10.1016/j.engfailanal.2022.106261

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

Myronova, I., Kovrov, O., Dudek, M., Voronkova, Y., & Kononenko, M. (2025). Environmental assessment of the impact of iron ore mine emissions on biological indicators of winter wheat. *IOP Conference Series: Earth and Environmental Science*, 1457(1), 012004. https://doi.org/10.1088/1755-1315/1457/1/012004

Otey, J., Company, P., Contero, M., & Camba, J. (2018). Assessment of Parametric Assembly Models Based on CAD Quality Dimensions. *Computer-Aided Design and Applications*, 16(4), 628–653. https://doi.org/10.14733/cadaps.2019.628-653

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

Psyuk, V., & Polyanska, A. (2024). The usege of artificial intelligence in the activities of mining enterprises. *E3S Web of Conferences*, 526, 01016. https://doi.org/10.1051/e3sconf/202452601016

Rastsvietaiev, V. O., Posunko, L. M., Shyrin, A. L., & Zheglov, S. S. (2015). Estimation of factors limiting efficiency of transport schemes while preparing coal reserves in Western Donbas mines. *Mining of Mineral Deposits*, 9(1), 117–123. https://doi.org/10.15407/mining09.01.117

Ravichandran, G. (2020). Finite Element Analysis. *Finite Element Analysis of Weld Thermal Cycles Using ANSYS*, 25–33. https://doi.org/10.1201/9781003052128-4

Sakurai, S. (2010). Modeling strategy for jointed rock masses reinforced by rock bolts in tunneling practice. Acta Geotechnica, 5(2), 121–126. https://doi.org/10.1007/s11440-010-0117-0

Sala D., & Bieda, B. (2024). Management of the Rare Earth Elements (REE) in the Global Economy: Neodymiun Case Study. Inżynieria Mineralna, 2(2 (52)). https://doi.org/10.29227/im-2023-02-53

Sala, D., & Bieda, B. (2021). Role of Stochastic Approach Applied to Life Cycle Inventory (LCI) of Rare Earth Elements (REEs) from Secondary Sources Case Studies. *Towards a Sustainable Future - Life Cycle Management*, 107–120. https://doi.org/10.1007/978-3-030-77127-0_10

Sobolev, V., Gubenko, S., Khomenko, O., Kononenko, M., Dychkovskyi, R., & Smolinski, A. (2025). Physical and chemical conditions for the diamond formation. *Diamond and Related Materials*, 151, 111792. https://doi.org/10.1016/j.diamond.2024.111792

Sosnowski, P., Dyczko, A., & Kamiński, P. (2024). Quality management in a 3D geological model – reliability of predicted hard coal quality parameters. E3S Web of Conferences, 526, 01003. https://doi.org/10.1051/e3sconf/202452601003

Stöcklein, J., & Kaliske, M. (2022). Thermo-hygro-mechanically coupled modelling of wood including two-phase moisture diffusion for transient simulation of wooden structures at mechanical and climatic loads. *Heat and Mass Transfer*, 59(1), 67–79. https://doi.org/10.1007/s00231-022-03178-2

Sun, X., Cai, F., Yang, J., & Cao, W. (2009). Numerical simulation of the effect of coupling support of bolt-mesh-anchor in deep tunnel. Mining Science and Technology (China), 19(3), 352–357. https://doi.org/10.1016/s1674-5264(09)60066-1

Symanovych, G., Astafiev, D., Vivcharenko, O., & Snigur, V. (2015). Increasing of yielding of frame-anchor support steadiness. *New Developments in Mining Engineering*, 45–48. https://doi.org/10.1201/b19901-9

Tereshchuk, R. M., Khoziaikina, N. V., & Babets, D. V. (2018). Substantiation of rational roof-bolting parameters. *Nauko-*

vyi Visnyk Natsionalnoho Hirnychoho Universytetu, (1), 19–26.

Tokarczyk, J. (2016). Method for Identification of Results of Dynamic Overloads in Assessment of Safety Use of the Mine Auxiliary Transportation System. *Archives of Mining Sciences*, 61(4), 765–777. https://doi.org/10.1515/amsc-2016-0052

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

Vlasov, S., Moldavanov, Y., Dychkovskyi, R., Cabana, E., Howaniec, N., Widera, K., Bąk, A., & Smoliński, A. (2022). A Generalized View of Longwall Emergency Stop Prevention (Ukraine). Processes, 10(5), 878. https://doi.org/10.3390/pr10050878

Vosoughifar, H., Madadi, F., & Rabiefar, A. (2017). Modified dynamic stress concentration factor for twin tunnels using a novel approach of FEM-scattering. Tunnelling and Underground Space Technology, 70, 30–41. https://doi.org/10.1016/j.tust.2017.07.006

Yegorchenko, R.R., Mukha, O.A., & Shirin, L.N. (2022). The methods to calculate expediency of composite degassing pipelines. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (4), 23–27. https://doi.org/10.33271/nvngu/2022-4/023

Zapukhliak, I., Zaiachuk, Y., Polyanska, A., & Kinash, I. (2019). Applying fuzzy logic to assessment of enterprise readiness for changes. *Management Science Letters*, 2277–2290. https://doi.org/10.5267/j.msl.2019.7.026

Zhai, W., He, Q., Bao, Y., & Cai, C. (2025). Suspended monorail system dynamics: fundamental and practice. *Railway Engineering Science*, 1–25. https://doi.org/10.1007/s40534-025-00403-6

Zienkiewicz, O. C., Taylor, R. L., & Zhu, J. Z. (2013). *The finite element method: Its basis and fundamentals*. Butterworth-Heinemann, 756 p.

SAŽETAK

Upravljanje parametrima okvirno-sidrenoga sustava podgrade u pripremnim iskopima za transport teškoga tereta jednotračnim željezničkim sustavom

Članak prikazuje sveobuhvatno istraživanje o upravljanju i optimizaciji okvirno-sidrenoga sustava podgrade u pripremnim jamskim iskopima namijenjenima transportu tereta velike nosivosti pomoću visećega jednotračnog željezničkog sustava. S intenziviranjem podzemne eksploatacije i sve većom primjenom teških transportnih sustava osiguranje stabilnosti i sigurnosti jamskih prostorija pod utjecajem dinamičkih opterećenja postaje jedan od ključnih inženjerskih izazova. U radu je predložena inovativna tehnologija podgrade koja se temelji na kombiniranome učvršćenju jednotračnih željezničkih sustava – spajanjem na tjemena metalnih okvira te izravnim sidrenjem u krovnu stijensku masu pomoću dubokih sidara. Cilj takva pristupa jest smanjenje dinamičkih naprezanja u krovini iskopa i povećanje ukupne pouzdanosti sustava podgrade. Radi procjene učinkovitosti predložene konstrukcije podgrade primijenjena je numerička metoda modeliranja kojom je simulirano međudjelovanje komponenti u dinamičkome sustavu „viseća jednotračna željeznica – podgrada – stijenska masa". Analiza ponašanja stijenske mase pri naprezanju i deformacijama provedena je primjenom softverskoga paketa SolidWorks Simulation. Tijekom simulacija sustavno su mijenjani različiti parametri, uključujući razmake između okvira podgrade, duljinu i dubinu usidrenja sidara te mehanička svojstva stijenske mase. Rezultati analize omogućili su određivanje racionalnih konstrukcijskih parametara koji minimiziraju deformacije i povećavaju nosivost podgrade. Posebno je utvrđeno da optimalna kombinacija razmaka okvira i konfiguracije sidara znatno smanjuje koncentracije naprezanja i poboljšava stabilnost pripremnih prostorija pod djelovanjem dinamičkih opterećenja nastalih kretanjem jednotračnih željezničkih kompozicija. Provedeno istraživanje pokazuje kako učinkovito upravljanje parametrima sustava podgrade može dovesti do povećanja sigurnosti, smanjenja potrošnje materijala i ubrzanja napredovanja jamskih radova. Dobiveni rezultati praktično su primjenjivi u projektiranju podzemnih transportnih ruta te se mogu ugraditi u normativne dokumente koji reguliraju projektiranje i primjenu podgradnih sustava u dinamički opterećenim rudarskim okruženjima.

Ključne riječi:
okvirno-sidrena podgrada, jednotračni željeznički transport, transport teškoga tereta, analiza naprezanja i deformacija, upravljanje rudarskom infrastrukturom, raspodjela dinamičkoga opterećenja

Author's contribution

Herasymenko Andrii (Doctor of Philosophy in Mining Engineering, Assistant Professor) - conceptualization, methodology, formal analysis, original draft; **Shyrin Leonid** (Doctor of Engineering, Professor) - supervision, data validation, review & editing; **Yegorchenko Rostyslav** (Doctor of Philosophy in Mining Engineering, Associate Professor) - data curation, software support, results visualization & investigation; **Iniutkin Ivan** (Candidate of Engineering Sciences, Associate Professor): - mechanical modeling, finite element simulation, technical validation; **Pazynich Yuliya** (Candidate of Political Sciences, Associate Professor) - literature review, environmental assessment, editing and proofreading. All authors have read and agreed to the published version of the manuscript.