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The first issue of the journal "Podzemni radovi" (Underground Mining Engineering) was published back in 1982. Its founders were: Business Association Rudis - Trbovlje and the Faculty of Mining and Geology Belgrade. After publishing only four issues, however, the publication of the journal ceased in the same year.

Ten years later, in 1992, on the initiative of the Chair for the Construction of Underground Roadways, the Faculty of mining and Geology as the publisher, has launched journal "Podzemni radovi". The initial concept of the journal was, primarily, to enable that experts in the field of underground works and disciplines directly connected with those activities get information and present their experiences and suggestions for solution of various problems in this scientific field.

Development of science and technique requires even larger multi-disciplinarity of underground works, but also of the entire mining as industrial sector as well. This has also determined the change in editorial policy of the journal. Today, papers in all fields of mining are published in the "Underground Mining Engineering", fields that are not so strictly in connection with underground works, such as: surface mining, mine surveying, mineral processing, mining machinery, environmental protection and safety at work, oil and gas engineering and many others.

Extended themes covered by this journal have resulted in higher quality of published papers, which have considerably added to the mining theory and practice in Serbia, and which were very useful reading material for technical and scientific community.

A wish of editors is to extend themes being published in the "Underground Mining Engineering" even more and to include papers in the field of geology and other geo-sciences, but also in the field of other scientific and technical disciplines having direct or indirect application in mining.

The journal "Underground Mining Engineering" is published twice a year, in English language. Papers are subject to review.

This information represents the invitation for cooperation to all of those who have the need to publish their scientific, technical or research results in the field of mining, but also in the field of geology and other related scientific and technical disciplines having their application in mining.

Editors

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Review paper

DESIGN AND OPTIMIZATION OF VENTILATION SYSTEMS FOR DEEP UNDERGROUND MINES

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Abstract: The combination of environmental factors in deep underground mines poses risks to worker safety and health while negatively affecting operational cost efficiency. As mines reach greater depths, maintaining safe and energy-efficient ventilation becomes a central engineering challenge due to elevated heat, gas accumulation, and airflow resistance. This paper aims to analyze and evaluate optimization strategies for deep underground mine ventilation systems, focusing on methods that enhance airflow performance, energy efficiency, and occupational safety. Through a comprehensive literature-based assessment, the study examines key optimization techniques, including ventilation-on-demand, dynamic fan control, computational fluid dynamics (CFD) modeling, and artificial intelligence (AI)-driven monitoring, to identify best practices for sustainable mine ventilation. Technological innovations such as automation, digital twins, and Internet of Things (IoT)-based control systems are also discussed for their role in enabling intelligent and adaptive ventilation management. The findings highlight that integrating optimization with modern technologies not only improves air quality and energy efficiency but also strengthens safety performance and environmental compliance in deep mining operations. Overall, this study provides an updated synthesis of global research and industrial practices to guide the design and optimization of ventilation systems that ensure both operational effectiveness and long-term sustainability in deep underground mines.

Keywords: Ventilation Optimization, Deep Underground Mining, Energy Efficiency, Automation, Airflow Management, Safety

1 INTRODUCTION

The global resource extraction industry relies heavily on deep underground mining to meet the growing demand for valuable minerals and metals, which must be obtained from ever deeper locations beneath the earth's surface (Liu et al., 2024). Mining operations that penetrate deeper into the earth face elevated challenges, which include managing dangerous heat levels, toxic gases, dust accumulation, and high humidity levels, all of which threaten worker safety and equipment functionality (Hardcastle and

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Kocsis, 2004). Deep mining environments with their high temperatures, limited airflow, and hazardous gas build-up require constant development of advanced ventilation systems (Shi et al., 2024).

Mine ventilation in deep underground operations performs essential duties beyond fresh air supply since it establishes the mining environment while ensuring worker safety and operational efficiency (Okechukwu et al., 2024). Ventilation systems perform the vital roles of removing toxic gases and explosive vapors while controlling airborne particles and managing heat stress to protect worker health and meet regulatory standards (Yang, Yao and Wang, 2022). The complexity of underground networks, which have been expanded through years of mining operations alongside existing infrastructure, requires urgent attention toward modernizing ventilation systems for optimization. Modern deep mining requires superior air quality and thermal management capabilities, which outdated or poorly controlled systems do not provide, thus driving the need for ongoing innovation in system design and operations (Roy et al., 2022).

Research developments, together with technological progress, have transformed deep mine ventilation practices during recent years through the combination of mine aerology evolution and digital monitoring and control systems, which enable intelligent, energy-efficient operations (Zhang et al., 2023). Current trends necessitate both resilient ventilation systems that adapt to changing underground conditions and sustainable approaches that decrease energy use alongside environmental degradation (Shriwas and Pritchard, 2020). The IoT, big data analytics, and advanced computational modeling represent emerging technologies that transform ventilation system management by facilitating real-time monitoring and automated control to optimize airflow while minimizing operational costs (Semin et al., 2020).

Despite these advances, there remains a need for a systematic synthesis of optimization strategies that directly target energy reduction, improved airflow performance, and safety assurance in deep underground mines. This paper aims to analyze and evaluate key optimization approaches for deep mine ventilation systems, emphasizing how technological innovations, including automation, digital twins, and intelligent control, support energy-efficient and safe operations.

The field of underground mine ventilation design requires balancing environmental and safety factors to maintain safe and healthy operations while maximizing efficiency. The ventilation design must manage hazardous gas and contaminant removal while regulating the mine's climate and adhering to regulatory standards to reduce environmental impacts and operational costs alongside emergency prevention and handling.

The complex challenges faced today create an essential and immediate need for a systematic examination of deep underground mine ventilation systems design and optimization. This investigation examines the basic concepts that guide mine ventilation alongside the primary goals and modern innovations propelling its development. The study will investigate essential technical and safety aspects along with environmental impacts related to ventilation system design while presenting a historical overview together with recognized best practices and modern optimization techniques based on new technology developments. The review will use comprehensive analysis to develop deeper insights into the engineering and management of modern ventilation systems that address deep underground mining challenges to enable safer and more sustainable resource extraction.

Following this introduction, a comprehensive literature review is presented to contextualize recent studies and practical developments in ventilation optimization. Subsequent sections detail optimization strategies, supporting technological innovations, industrial case studies, and future challenges shaping the evolution of deep mine ventilation systems.

2 LITERATURE REVIEW ON DESIGN AND OPTIMIZATION OF VENTILATION SYSTEMS FOR DEEP UNDERGROUND MINES

This section synthesizes recent studies from 2020–2024 relevant to the optimization and design of deep mine ventilation systems.

The number of articles covered in this review for the design and optimization of ventilation systems for deep underground mines are shown in Figure 1 from 2020 through 2024.

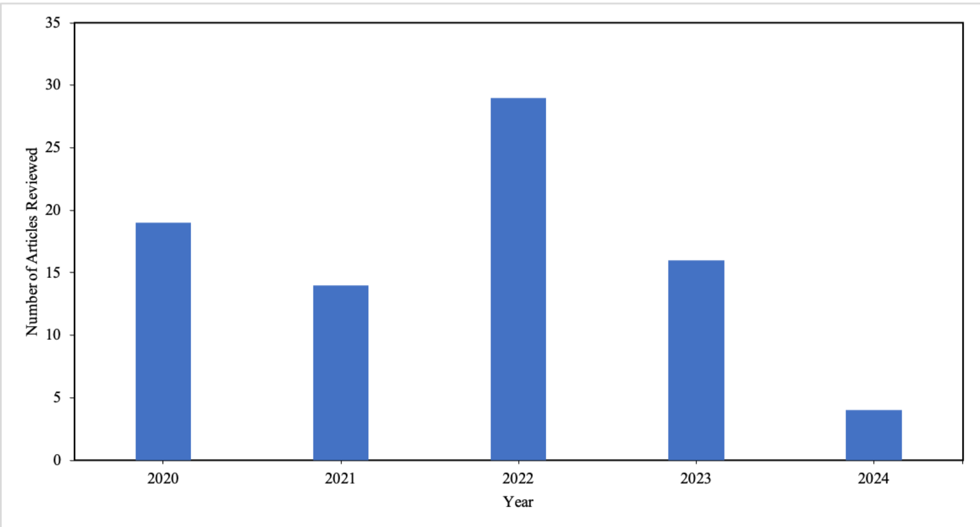

Figure 1 Articles reviewed (2020-2024) for the design and optimization of ventilation systems for deep underground mines

Table 1 below shows a quantitative distribution by publisher of the number of articles related to design and optimization of ventilation systems for deep underground mines.

Table 1 Number of articles from different publishers reviewed for design and optimization of ventilation systems for deep underground mines

Publisher	**Number of Articles Reviewed**
MDPI	21
Springer	16
Elsevier	9
Taylor & Francis	5
IOP Publishing	4
Wiley	3
EDP Sciences	2
Frontiers	2
IEEE	2
Polish Academy of Sciences	2
The Southern African Institute of Mining and Metallurgy	2
ACS Publications	1
Brazilian Association of Metallurgy, Materials and Mining	1
Empress Catherine II Saint Petersburg Mining University	1
Journal of Computers	1
Lembaga Penelitian dan Pengabdian Masyarakat (LPPM)	1
National Mining University of Ukraine	1
PLOS	1
Polskie Towarzystwo Przeróbki Kopalin (Polish Mineral Engineering Society)	1
Russian Mining Industry Journal	1
Sage Journals	1
Universidad Nacional de Colombia	1
University of Belgrade	1
University of Montevideo	1
University of Zielona Góra	1
Total	**82**

The Computational Energy Dynamics (CED) model created by Danko et al. (2020) simulates temperature and heat flow in mine ventilation networks through integration of heat capacity principles and variable rock conduction along with latent heat effects. The model they created that incorporated a thermal flywheel effect to manage time-dependent temperature changes successfully mirrored real-world climate conditions with high precision, which helped optimize ventilation system thermal performance. Nadaraju et al. (2020) explored mine ventilation systems from an environmental and energy standpoint through simulations that optimized Ventilation Air Methane (VAM) abatement processes to decrease low-concentration methane (CH_4) emissions. The simulation results indicated that optimization techniques successfully reduced emissions while simultaneously boosting energy efficiency and cutting operational expenses, thus providing combined advantages in safety and sustainability. Sridharan and Sastry (2020) focused their study on aerodynamic aspects to reveal major discrepancies in current shock loss factor models that calculate pressure drops from mine car trains. They developed improved prediction models through CFD combined with scale model analysis, which decreased overestimations and enhanced simulation fidelity, leading to more effective airflow planning.

Tutak and colleagues (2020) conducted research on the actual effects when an active longwall mining site switched from U-type to Y-type ventilation infrastructure. The Y-type system successfully decreased CH_4 concentrations but also unintentionally increased spontaneous combustion risks because it allowed more oxygen to reach the goaf. In contrast, Yi et al. (2020) tackled the problem through computational methods by using ANSYS CFX to run CFD simulations, which helped optimize blowing and exhaust duct arrangements at a mining face. Numerical experiments showed that strategic placement of ducts and adjustments to mass flow rates effectively minimized air stagnation and contamination through design-dependent airflow dynamics. Jia et al. (2020) developed an algorithm for network-level optimization that merges the independent path method with an adaptive genetic algorithm to improve and simplify the visualization of ventilation network feature graphs. The new method improved the visualization of airflow patterns while decreasing graphical complexity and enabled better management decisions for airflow adjustments and resistance control.

Wei and colleagues (2020) performed numerical simulations and laboratory experiments to study how ventilation duct height and wind velocity affect airflow structure and dust movement in underground coal mine headings. The research indicated improved dust extraction and reduced dangerous vortices when the duct was placed at 0.625 roadway height with a minimum 2 m distance from the working site. The research conducted by Cahyono (2020) examined the technical aspects of planning a ventilation system for the W Undercut development at PT Freeport Indonesia. Through engineering software analysis, he determined that the airflow requirement stood at 180 m^3/s for six working faces while calculating head loss and system resistance and proposed auxiliary fan installation to meet the ventilation standards. Shriwas and Pritchard (2020) examined modern ventilation monitoring and control systems through a technological lens, pinpointing research gaps in sensor accuracy and real-time data integration for Industrial Internet of Things (IIoT) applications while noting successful implementations in Canadian, Australian, and U.S. mining operations.

Pach et al. (2020) explored reversal ventilation as a fire hazard mitigation technique and performed numerical simulations to evaluate its ability to regulate CH_4 levels during emergency evacuations. Implementation of full operational control over ventilation fan subnetworks with reversal ventilation was proven to reduce escape route lengths and maintain CH_4 levels within safe boundaries, thus improving emergency response capabilities, according to their findings. The work of Liu et al. (2020) concentrated on mine ventilator system stability improvement through a universal ventilator model development and Adaptive Chebyshev Neural Network (ACNN) controller implementation. The ACNN method achieved high precision with a mean absolute error below 0.02 and showed adaptability to unforeseen disruptions during simulation tests verified by Lyapunov stability criteria and surpassed conventional control methods in dynamic mining conditions. The research team led by Zhu in 2020 created an advanced ventilation optimization model that combined mine classification systems with gas emission analysis and coal dust explosion risk assessment. The combination of MATLAB and Lingo software enabled them to ascertain minimum air volume needs for various mining faces and achieve optimized air supply at 1491.18 m^3/min to set safety ventilation guidelines for high-risk mining operations.

The study by Guo et al. (2020) examined U-type and Y-type ventilation systems in deep coal mines and found that although U-type systems showed lower initial airflow temperatures, the Y-type systems offered better long-term thermal management for adjacent working areas. The research highlights how rock wall roughness and ventilation duration impact heat transfer while proving that the Y-type system better preserves cool and stable mine conditions through time. Kuyuk et al. (2020) investigated the ventilation problems of ultra-deep Arctic mines while proposing a sustainable closed-loop bulk air conditioning system powered by renewable energy. Their research revealed that using geothermal gradients to achieve simultaneous heating and cooling led to substantial fossil fuel savings and improved energy efficiency while providing a sustainable approach designed for cold climates. In 2020, Zhong et al. concentrated on computational ventilation system design and developed an innovative solution method using Minimum Independent Closed Loops (MICL) to improve airflow distribution modeling. The improved circuit division method resulted in accelerated iteration convergence and increased computational stability for complex networks, which provides a strong optimization tool for ventilation infrastructure.

Szczurek and colleagues (2020) assessed underground mine mobile machinery cabins' microenvironment and found traditional ventilation systems insufficient for health and safety compliance due to ambient air pollutants entering the space. A team developed an analytical air quality model that included a hybrid solution of ventilation combined with air-conditioning and filtration systems along with personal clean air supplies to maintain safe exposure levels for operators in all external conditions. Saki and colleagues in 2020 developed optimization methods for gob ventilation boreholes (GVBs) in longwall mining to enhance CH_4 extraction capabilities while also preventing explosive gas zones

(EGZs). CFD simulations allowed them to assess the impact of borehole location, diameter, vacuum pressure, and GVB activity levels on gas extraction, which led to the understanding that careful adjustment of these variables provided optimal gas removal results and improved safety conditions. Research by Liu et al. (2020) provided insights into longwall gob material behavior by testing rock compaction experimentally to understand their compaction properties and permeability. Research showed that when gob compaction increased under stress conditions, it changed its porosity and permeability, which led to different patterns of gas transport pathways. The researchers developed a predictive framework for mine-scale ventilation planning by measuring how material deformation influences airflow and gas dispersion patterns.

The Boliden Garpenberg mine implemented a model-based control strategy using a data-driven dynamic model created from both historical operational data and step-change experiments, according to Sjöström et al. (2020). The implementation of their optimized control system led to a 40% reduction in energy consumption for main and booster fans while enhancing airflow controllability. Tu et al. (2021) undertook an analysis of heat sources combined with evaluations of ventilation strategies that incorporate free-cooling techniques in mineral mines. The study showed that both segmented cooling (SC) and heat shield-assisted centralized systems (CCHS) made temperature profiles at working faces better, while indirect evaporative cooling (IEC) increased the annual energy efficiency ratio (EERann) by up to 32% based on ambient conditions. Li et al. (2021) utilized numerical simulation to evaluate thermal performance in an excavating roadway through a fully coupled model that integrates moving mesh methods. The study determined that increasing airflow volume only provides minimal cooling benefits, while reduced duct diameter and shorter outlet-to-face distances create adverse thermal effects.

Heriyadi and Zakri (2021) examined effective air ventilation systems as a crucial factor for underground coal mining operations in Sawahlunto City. The researchers established a direct relationship between insufficient ventilation and workplace accidents like CH_4 gas explosions, which caused deaths from 2009 to 2017. The research demonstrated that managing air quality and quantity through a well-maintained ventilation system enhances workplace safety and worker productivity by increasing confidence and comfort levels. The 2021 study by Zgrzebski et al. explored the increasing aerological hazards that emerged at KGHM Polska Miedź S.A. during the expansion of mining operations to deeper levels. Their efforts concentrated on improving ventilation systems to reduce the hazards associated with toxic gases and dust particles. Research findings revealed that optimizing airflow management along with real-time monitoring systems decreased dangerous gas levels and thus enhanced miner security. The research conducted by Li et al. (2021) explored the effects of ventilation on the extent of excavation damaged zones (EDZ) within high-temperature tunnels in Enhanced Geothermal Systems. When ventilation systems were used in high-temperature settings, they induced tensile stress in surrounding rocks, which altered the size and shape of the EDZ. The research demonstrated that ventilation control is essential for managing damage zones within deep mines with high temperatures, which requires ventilation system designs to account for both thermal properties and mechanical forces.

Wu and his colleagues (2021) explored how dual-radial swirl shielding ventilation can be optimized to manage dust levels in fully mechanized excavation faces. The study used numerical simulations along with experimental validation to identify that a blowing and suction air volume ratio of 1.5 yielded optimal dust control, which provided essential knowledge about managing airflow in mines. The research by Hurtado et al. (2021) aimed to improve the connection between intake fans and mine ventilation shafts through optimization to minimize energy losses while enhancing airflow volume. Utilizing CFD simulations, researchers determined optimal guide vane configurations and elbow curvature ratios, which showed possibilities for saving energy and improving airflow in ventilation systems. The research extended its usefulness to multiple engineering sectors outside of mining. Xin et al. (2021) evaluated the cooling performance of the far-forcing-near-exhausting (FFNE) and near-forcing-far-exhausting (NFFE) auxiliary ventilation systems using field measurements and simulations. The NFFE configuration achieved superior performance compared to the FFNE system when the exhaust-to-forcing volume flow rate (Re/f) reached 1.5 alongside optimal duct placement. The study demonstrated that proper ventilation configuration plays a critical role in ensuring thermal comfort and safety for underground mining operations.

Through numerical simulation with FLUENT, Jiang et al. (2021) assessed different tunnel drilling ventilation systems and found that the “long pressure and short suction” ventilation layout enhanced dust control efficiency near the work area by about 60%, which played an essential role in maintaining health standards and visibility in long single-ended tunnels. Iliinov et al. (2021) explored strategic optimization of mine-wide ventilation systems to accommodate growing mechanization demands in deep underground mining operations. Through staged ore block commissioning, the team achieved localized airflow control, which resulted in a 30% reduction of air travel paths and at least a 20% pressure drop decrease while improving airflow efficiency without extra energy consumption. Gao et al. (2021) used both CFD and physical modeling to establish the best blowing-to-suction flow ratio for wall-mounted swirling ventilation systems in mechanized coal excavation faces. The optimal blowing-to-suction flow ratio of 0.8 delivered the best dust suppression performance, reducing total dust by 90.33% and respirable dust by 87.16% through improved airflow disturbances and radial containment.

Janus (2021) created an advanced numerical simulation model that includes real longwall geometries along with goafs and their porosity and permeability properties to analyze airflow within a u-ventilated longwall system. The research model provided detailed insights into turbulent airflow patterns, which became a powerful way to improve ventilation systems. Si et al. (2021) demonstrated how variable fuzzy theory can optimize sensor placement for dynamic ventilation monitoring. The investigative team identified ten optimally placed sensors that monitor air quantity across 19 ventilation branches, showing an effective solution for continuous accurate airflow management in complex networks. The research of Obracaj et al. (2021) focused on controlling CH_4 emissions by implementing an overlap auxiliary ventilation system for mechanized roadways. CFD simulations demonstrated that maintaining an overlap zone length between 5 and 10 meters reduced CH_4 accumulation while showing how return air vortices near the dust scrubber affected outcomes.

Xie and colleagues (2022) performed a COMSOL Multiphysics CFD simulation to study how carbon monoxide (CO) and sulfur dioxide gases move through small, low-pressure roadway systems inside non-metallic mines located in Hunan Province. Their study showed that tunnel design and airflow speed played crucial roles in pollutant build-up through vortex patterns, and they proposed enhancements to structural ventilation systems through auxiliary pipes. The research by Wu et al. (2022) extended the analysis of CO migration after blasting in high-altitude tunnels with an inclined shaft where CFD simulations showed that different fan modes altered vortex positions and CO distribution. The researchers introduced a dual-phase ventilation approach, which led to 18% better ventilation efficiency (VE) and a 33% decrease in energy usage. Niewiadomski and colleagues (2022) conducted research on CH_4 dispersion in longwall mining through the simulation of 32 different ventilation setups using ANSYS Fluent software. The research showed auxiliary systems generally performed well, but the exact positioning of the brattice and air duct did not affect CH_4 levels unless they were near the tailgate caving line.

The study by Nguyen et al. (2022) evaluated the Thanh Cong–Cao Thang coal mine's ventilation system in Vietnam and found structural and operational inefficiencies after the mine's consolidation, which led to recommendations for routine evaluations and system improvements alongside personnel training to enhance airflow and diminish safety risks. Wang et al. (2022) investigated the effects of natural wind pressure changes on ventilation stability within the deep Tangkou Coal Mine using field measurements and FLUENT simulations to demonstrate the potential of atmospheric pressure variations to alter airflow direction and underscored the critical need for continuous environmental monitoring to avoid gas buildup. Jacobs et al. (2022) enhanced mine ventilation design and optimization through their calibrated digital twin model for South African mines, which allowed predictive analysis of thermal, dust, and gas hazards for proactive ventilation strategy optimization over the mine's lifespan.

Wang et al. (2022) created an advanced path algorithm for controlling airflow in multi-fan mine ventilation systems, which addresses the shortcomings of current algorithms, including false paths and poor regulator placement, and their case study confirmed the algorithm's success in airflow optimization and safety improvement. Kohmann and Silva (2022) researched airflow patterns in a Brazilian coal mine through measurements and Ventsim Lite simulations, which confirmed regulatory compliance yet revealed potential airflow distribution improvements, especially in densely populated worker areas, along with suggestions for routine monitoring and greater sampling frequency. Bosikov et al. (2022) conducted research on mathematical modeling and control mechanisms for gas-dynamic processes in mine ventilation systems and introduced an algorithm that combines static and dynamic characteristics to optimize airflow management while reducing energy consumption; their findings highlighted the importance of understanding aerodynamic parameter dependencies throughout the ventilation network.

Kumar et al. (2022) implemented VoD in Indian underground coal mines, which, through dynamic ventilation fan adjustments and constant-speed reduction using variable speed drives (VSD), achieved annual energy savings of 1,070,618 kWh and reduced greenhouse gas emissions by 37%. Guo and colleagues (2022) used Fluent software to model ventilation designs for extended mountain tunnels and found that both reducing duct-to-face distance and enlarging duct diameter increased CO extraction effectiveness, while optimal jet fan placement near contamination points improved ventilation operations by preventing airflow short-circuiting. Xin et al. (2022) demonstrated a groundbreaking use of Data Envelopment Analysis (DEA) to assess air supply efficiency in deep mine headings through Cooling Efficiency (CE) and VE metrics. Through their simulations, researchers established that the most effective thermal balance requires an air supply temperature differential of 6 °C.

Saeidi and Allen's 2022 research explored how transitioning to battery-electric mobile equipment affects ventilation systems by demonstrating reduced harmful emissions from electric fleets, which reduced air volume needs but increased focus on heat management and proper air velocity. The research by Vives et al. (2022) applied CFD to refine auxiliary ventilation layouts by evaluating four different duct placement options to measure airflow and heat dissipation effectiveness; they found through simulations backed by real mine data that duct location near the working face was critical and that the optimal duct positioning depended on specific temperature or airflow goals. Janus and Ostrogórski (2022) focused on modeling mine tunnel geometries through terrestrial laser scanning (TLS), which they proved to be the most accurate method among five tested approaches for cross-sectional area measurement essential for ventilation calculations.

The research by Boantă and Tomescu (2022) involved using the CANVENT software together with the Hardy Cross method to model airflow optimization in the Vulcan Mine’s complex ventilation system of 251 nodes and 300 branches; their work resulted in better air distribution in real-time operations and increased safety through predictive responses to potential risks. The research by Chikande et al. (2022) resulted in a VoD system that operates in a Zimbabwean platinum mine with IoT technologies for air quality and worker monitoring, which achieved 23% power savings and 6% productivity growth, demonstrating digital transformation advantages in energy efficiency and operational performance. Nie et al. (2022) combined CFD with the entropy weight method to evaluate dust-laden airflow dispersion and absorption during sub-regional coal cutting operations, establishing three dust behavior zones and an optimal air-absorption volume of 575 m^3/min for efficient dust control.

The case study by Słota and Słota (2022) examined tunnel ventilation design with special attention to how fan parameters and duct configurations affect both airflow efficiency and energy usage. The study demonstrated that wider duct diameters combined with dual installations led to lower ventilation power needs, while parallel duct systems resulted in 30-50% higher energy usage, which emphasized the need for strategic duct sizing and layout choices. Gao et al. (2022) employed fractal analysis to create a new calculation model for tunnel wall roughness-induced ventilation friction resistance, which showed traditional empirical models did not adequately estimate airflow resistance. Through simulations with a mere 3% error margin, researchers produced a more dependable foundation for intelligent ventilation modeling in rough rock environments. Liu et al. (2022) developed an efficient graphical algorithm to optimize ventilation monitoring through sensor placement while introducing the "independent cut set" method, which allowed airflow reconstruction with sensors installed in less than 30% of tunnels. The algorithm tested in a large-scale mine maintained accurate air volume estimation through reduced sensor deployment, which led to better cost-efficiency and operational effectiveness.

Xia et al. (2022) designed a three-dimensional (3D) CFD model to optimize ventilation shafts in large-scale underground cavern groups for pumped-storage power plants and discovered that an 8-meter diameter shaft with 80° inclination resulted in the best airflow distribution supported by on-site validation. Chen et al. (2022) explored fire safety in underground tunnels by analyzing how water curtains interact with mechanical ventilation through CFD-based fire simulation models. Through their research they established that setting mechanical ventilation at 0.8 m/s was essential for enhancing the smoke control capabilities of the water curtain, which resulted in better tunnel visibility and lower CO levels during fire incidents. Li and their team (2022) introduced the Bare-Bones Particle Swarm Optimization algorithm (BBPSO-Para-Improved), which targets power consumption reduction and air demand maximization through dynamic penalty terms and strategic optimization to improve convergence efficiency in complex ventilation networks. Their approach received validation from practical mining operations, where it proved to excel in economic savings as well as safety improvements. Yu and Shao (2022) developed an Improved Equilibrium Optimizer (IEO) specifically for energy efficiency, which combines chaotic mapping and Gaussian disturbance techniques. The implementation of their algorithm at Wangjialing Mine resulted in a 17.83% energy savings along with substantial cost reductions, thereby demonstrating the value of energy efficiency and economic operations. The team led by Nie et al. (2022) worked on optimizing ventilation systems for tunnels by studying the effects of airflow rate and duct-wall distance on dust control from an environmental and health safety perspective. The combination of numerical simulations and field measurements revealed that press-in airflow reduction to 150 m³/min along with duct placement 1.5 meters from tunnel side walls dramatically reduced dust spread while improving air quality near excavation areas.

Zhang and colleagues used CFD simulations in 2022 to determine the best arrangement for dedusting air ducts in mechanized excavation work and found that duct location played a critical role in controlling dust diffusion and removal effectiveness. Optimal dust suppression was achieved when the duct was placed on the roadway's opposite side and kept 4–5 meters away from the tunneling head, according to their findings. Szlązak and Korzec (2022) suggested a modular fan station design for existing mine shafts to address the inefficiencies of oversized main fans during decommissioning. Polish coal mines saw substantial energy consumption reductions after implementing this solution, which proved both scalable and cost-effective. Hao et al. (2022) introduced a multi-branch joint adjustment approach based on sensitivity analysis to improve traditional ventilation-on-demand system performance. The implementation of a sensitivity change rate matrix together with Lagrangian interpolation enabled them to build a comprehensive dispatching model that provided precise and stable regulation of air volume across multiple branches. The potential application of their method to emergency response planning expanded its operational usefulness.

The research conducted by Hu and colleagues in 2023 involved safety optimization through experimental and numerical analysis of smoke movement within downward ventilation patterns during fire situations. The team discovered that enhancing fan power led to increased fire dynamics and established a critical wind speed threshold of 1.8 m/s where fire wind pressure matched fan output to support emergency planning strategies. Yan and colleagues (2023) created a sensor layout optimization method for underground ventilation systems through DETMAX and Tabu search algorithm integration, which enhances real-time airflow measurement accuracy and reduces both error and cost. The researchers demonstrated their model's superior monitoring efficiency and system intelligence performance by validating it against traditional algorithms such as Monte Carlo and Ant Colony methods through data collected from the Wangjialing coal mine. The 2023 research by Semin and Levin included mathematical modeling of air distribution across different ventilation modes in a potash mine with a U-tube design while factoring in shock losses and airflow reversals. Shock losses played a major role in air redistribution during ventilation mode changes, according to their study, while their model showed accurate predictions within 15% relative error when validated by experimental results.

Stolbchenko et al. (2023) developed a mathematical model to minimize external air leakage at the main ventilation unit by optimizing the interaction between main and counteracting fans. The study revealed that combining a 40° blade angle for the main fan with a 33° angle for the counteracting fan significantly decreased leakage while ensuring stable underground airflow, which enhanced both safety and efficiency. Through CFD analysis, Adhikari et al. (2023) determined that forced ventilation systems achieve five times better fume dilution than exhaust systems and found that both muckpile porosity and explosive types played significant roles in determining dilution time. Chen et al. (2023) implemented ANSYS-Fluent to optimize CFD models for reducing high temperatures in coal mining areas. Through their research they established that 36.81 m^3/s of air volume and 298 K temperature were optimal for their purposes and suggested a spray cooling system, which lowered pavement temperatures by 0.5–1°C to improve summer ventilation.

Bosikov and team (2023) presented a new analysis method using mathematical statistics and probability theory to study gas-dynamic processes while improving fire safety through ventilation network modeling, which demonstrates how diagonal connections affect air distribution and CH_4 management. Field experiments at Mine 31 confirmed their work, which introduced a spherical ventilation network design to improve critical connection identification and fire hazard prevention in CH_4-rich coal beds. Swanepoel et al. (2023) examined project-level decision-making processes through multi-criteria decision-making frameworks analytic hierarchy process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to determine environmental improvement priorities for deep-level mines. Their simulation-based analysis showed surface refrigeration as the best option for thermal comfort, and their method offered a systematic approach to balance cost with implementation time and risk while considering workers' conditions. Lian and Qi (2023) developed an energy optimization solution that uses a ventilation control model that integrates operational constraints and an improved Grey Wolf optimization algorithm. The approach implemented at Tangshan A Group B Coal Mine achieved its dual aim of decreasing energy consumption and maintaining necessary airflow levels through complex branched ventilation systems.

The study by Wróblewski et al. (2023) generated precise geometric models of mining excavations from 3D laser scanning data and incorporated these models into CFD simulations to study airflow patterns. The study showed that Light Detection and Ranging (LiDAR)-based geometries improved simulation precision in complex ventilation networks, which allowed for more accurate air velocity predictions and enhanced operational safety. Agson-Gani et al. (2023) approached the issue of airflow simulation through porous regions by integrating a conjugate porous media model into existing mine ventilation network software. The research presented a new friction factor coefficient for broken rock-filled drawpoints, which validation against 3D CFD models proved achieved more than 99% reduced computation time while preserving accuracy for real-time mine environment simulations. Estrada and Manzano (2023) used Ventsim 3D software for long-term ventilation planning at Santander Mine, which produced airflow rates at 102% of the necessary capacity through precise simulation scenarios. They implemented practical solutions by analyzing real mine data, which showed Ventsim enabled detailed airflow and pressure visualizations to help future system optimization and regulatory compliance.

The researchers Szlązak et al. (2023) developed strategies for CH_4 hazard control by designing ventilation and drainage systems for coal seams 404/1 and 403/1 located in southern Poland. The team studied CH_4 emission forecasts, which identified maximum emissions of 134.34 m^3/min and proved the requirement for U-type ventilation systems that operated with 38.3–40.6% efficiency while suggesting CH_4 capture for power generation to improve system performance. Kashnikov and Kruglov (2023) created a fuzzy logic-based automatic control method to tackle ventilation control issues at the 3RU mine of OAO Belaruskali. The study based on simulations demonstrated that fuzzy logic controllers led to enhanced airflow regulation while avoiding fresh air deficits and reducing main fan power consumption through a responsive and adaptive optimization process. Shao and colleagues conducted a 2023 study that tackled thermal hazard mitigation in deep metal mines through the combination of refrigeration technologies and air cycling systems. Through experimental and simulation-driven analysis backed by artificial neural network modeling with <5% prediction error, researchers showed improved energy efficiency and cooling effectiveness while the heat transfer rate of main exchangers increased by up to 16.38% during variable fan operation.

A 2023 study by Li et al. examined how damper systems react to gas explosion impacts using numerical simulations to test damper performance with different ventilation-regulating window configurations. Research findings demonstrate that damper displacement and stress depend significantly on the presence and size of ventilation windows, which informs safer design approaches for underground ventilation systems. Ihsan and colleagues (2024) researched VoD systems using adaptive neuro-fuzzy inference systems (ANFIS) to simultaneously enhance fan power efficiency and reduce hazardous gas concentrations. Laboratory-scale experiments showed that fan energy consumption decreased by 43% while ensuring safe ventilation conditions through AI-based systems. The 2024 study by Wan analyzed intelligent ventilation systems design through automation techniques and sensor deployment to enhance air quality control and disaster response capabilities. He developed optimization strategies incorporating remote control systems and intelligent air distribution to help mitigate disaster risks. Through the use of Back Propagation Neural Networks (BPNN) and CFD simulations, Zhang et al. (2024) created models that predicted toxic fume migration while identifying wind velocity as a key factor for determining migration time. The developed models demonstrated exceptional accuracy ($R^2 = 0.9945$), which provided essential knowledge to advance ventilation systems for toxic fume control. Finally, the authors Ilić and Petrović (2024) applied IIoT techniques to improve ventilation management in Serbian coal mines through real-time monitoring and automation strategies to boost safety and efficiency. Their study showed how IIoT technologies could both prevent hazardous events and boost mine ventilation system management.

The reviewed studies highlight optimization as a central theme, motivating the analysis of specific strategies and technologies in the following sections.

3 KEY OPTIMISATION STRATEGIES IN DEEP MINE VENTILATION SYSTEMS AND THEIR UNDERLYING PRINCIPLES

Building upon insights from recent literature, this section outlines the primary optimization methods currently used in deep underground mine ventilation. Ventilation systems in deep underground mines encounter a complex set of problems due to intricate underground networks that grow with depth and increased rock temperatures along with higher humidity levels (Hardcastle and Kocsis, 2004; Hancock, 2019). The environmental conditions present in deep mines pose risks to mine worker safety and health while simultaneously reducing mining operations' efficiency and cost-effectiveness (Roy et al., 2022; Kamyar et al., 2016). Mine management must prioritize ventilation system optimization to deliver fresh air effectively while diluting hazardous gases and removing heat and decreasing energy consumption (Mapeta, 2020; Parra et al., 2006). The process utilizes several strategies that combine technology with planning and monitoring techniques together with decision-making approaches to respond to the changing demands of deep underground mining environments (Kamyar et al., 2016; Sjöström et al., 2020).

3.1 Ventilation on Demand (VoD)

VoD dynamically adjusts airflow patterns according to immediate mining operations, equipment status, and worker positions (Saleem, 2025). VoD systems optimize energy use and operational performance by directing ventilated air to active mining areas while minimizing airflow in inactive zones without sacrificing safety standards (Saleem, 2025; Sjöström et al., 2020). Advanced VoD systems that integrate IoT controls with AI automation will boost both responsiveness and sustainability within ventilation networks (Saleem, 2025). The primary technical benefit of this system is its significant decrease in excess airflow that typically occurs with traditional fixed-flow setups (Sjöström et al., 2020).

3.2 Integrated Planning and Dynamic System Design

Mine development demands that ventilation systems undergo corresponding evolution for efficient system optimization (Swanepoel et al., 2023). Integrated planning utilizes surveys and baseline data along with predictive models to create adaptable airflow routes while positioning ventilation raises and fans optimally to support future expansions of the mine (Kamyar et al., 2016). Dynamic design maintains essential airflow during worst-case conditions when mine geometry and production stages shift, thus upholding worker safety and regulatory standards.

3.3 Computational Modelling and Simulation

3D mine ventilation modeling relies on the sophisticated capabilities of network simulators and CFD tools according to modern optimization practices (Du Plessis et al., 2013; Nie et al., 2018). The predictive modeling capabilities of these systems enable engineers to examine airflow patterns, heat transfer rates, and gas dispersion to optimize fan placement and assess the performance of changes across different operational scenarios (Maleki, Sotoudeh and Sereshki, 2018). The use of simulation-based research enables the effective integration of cooling systems, which become essential in deep mines with high temperatures (Nie et al., 2018).

3.4 Advanced Fan and Refrigeration Controls

Proper management of primary and auxiliary fans together with refrigeration plants stands as another vital approach for optimization (Parra et al., 2006; Webber-Youngman, 2005). The techniques used for ventilation control involve dynamic fan speed adjustment through variable frequency drives together with automated switching that responds to demand cycles and intelligent cooling system management during periods of low demand like night shifts and holidays (Webber-Youngman, 2005). These actions ensure ventilation supply meets mine requirements while reducing electrical power usage (Dello Sbarba, 2012.

3.5 Continuous Monitoring and Adaptive Controls

Real-time tracking of essential ventilation parameters, including airflow, temperature, humidity, and gas concentrations, forms the basis of successful optimization strategies (Liu et al., 2024; Shriwas and Pritchard, 2020). Mine ventilation control systems process data collected by advanced sensor networks and perform automated or semi-automated adjustments to maintain optimal indoor air quality while mitigating hazards immediately (Liu et al., 2024). This monitoring system enables preventive maintenance and fast fault detection, which minimizes operational interruptions and strengthens system resilience (Saleem, 2025).

3.6 Multi-Criteria Decision-Making and Project Prioritisation

Optimization methods for ventilation investment evaluation and project prioritization frequently employ multi-criteria decision-making frameworks to balance safety requirements with cost constraints and energy efficiency goals (Swanepoel, 2023). These methodologies help mine managers allocate resources effectively by assessing practical considerations including regulatory compliance, hazard mitigation, lifecycle cost, and technical feasibility (Swanepoel, 2023).

3.7 Energy Efficiency and Demand Management

Deep underground mines typically face high operating energy expenses, which leads to the implementation of various demand-side management techniques (Kamyar et al., 2016; Webber-Youngman, 2005). The operational schedule for non-essential fans, together with peak energy demand management through equipment switching during high grid demand periods and the implementation of energy-efficient motors and drives, makes up these measures (Webber-Youngman, 2005). Mining operations achieve lower operational expenses and carbon emissions through these measures (Dello Sbarba, 2012).

3.8 Integration with CH_4 Recovery and Environmental Innovations

The optimization of mining operations includes the recovery of CH_4 from ventilation air as well as its utilization, which helps reduce explosion hazards and lowers greenhouse gas emissions in coal mines (Acuña and Lowndes, 2014). Ventilation systems now merge heat recovery technologies with environmental controls, which leads to beneficial outcomes in terms of energy conservation and safety while meeting environmental standards (Dello Sbarba, 2012).

3.9 Technical Impact and Documented Outcomes

Case studies show that optimization strategies deliver real improvements in deep mine VE along with safety and cost management (Saleem, 2025; Parra et al., 2006; Oosthuizen, 2020). The deployment of VoD systems combined with adaptive controls has achieved significant energy savings without compromising health and safety standards in mining operations (Saleem, 2025; Sjöström et al., 2020). Site-specific ventilation inefficiencies were resolved through simulation-driven design improvements that led to better environmental conditions throughout the mine (Maleki, Sotoudeh and Sereshki, 2018; Oosthuizen, 2020). Ventilation upgrades prioritized and managed through data-driven frameworks achieve optimal results while staying within both budgetary limits and regulatory requirements (Swanepoel, 2023). Advanced systems integrate real-time data with automation technology to deliver predictive maintenance features and minimize downtime while strengthening resilience against ventilation system failures (Liu et al., 2024; Saleem, 2025).

Table 2 Major Optimisation Strategies and Their Benefits

Strategy	Principle	Key Benefits
VoD	Dynamic airflow allocation	Large energy savings, targeted hazard control
Integrated Planning & Dynamic Design	Adaptive system evolution	Sustained compliance, effective future-proofing
Computational Modelling & Simulation	Data-driven optimisation	Bottleneck identification, efficient design changes
Advanced Fan & Refrigeration Controls	Automated demand response	Minimized energy, controlled climate
Monitoring & Adaptive Controls	Real-time data integration	Prompt hazard mitigation, improved maintenance
Multi-Criteria Decision-Making	Balanced project ranking	Optimized resource use, prioritized improvements
Energy Efficiency & Demand Management	Cost-effective operation	Reduced energy costs, lower environmental impact
Environmental Integration & CH_4 Recovery	Safety & sustainability	Enhanced air quality, reduced greenhouse gases

4 TECHNOLOGICAL INNOVATIONS IN DEEP MINE VENTILATION SYSTEMS

While optimization defines the goal, emerging technologies provide the means to achieve it. The following innovations enable smarter, more energy-efficient ventilation systems. Challenging conditions of deep underground mining operations have led to major technological developments in ventilation systems during recent years (Ranjith et al., 2017). The progression of these systems demonstrates persistent efforts to boost safety and energy efficiency while improving operational reliability and protecting the environment in complex underground networks (Onifade, Said and Shivute, 2023).

4.1 Integration of Intelligent Monitoring and Fault Diagnosis

Deployment of intelligent technologies for ventilation fault diagnosis stands out as one of the major foundational innovations (Liu et al., 2024). Current ventilation systems integrate numerous sensors and sophisticated data processing capabilities, which support ongoing assessment and examination of essential mine parameters throughout the entire mine (Liu et al., 2024). The implemented technology detects faults at an early stage and provides actionable data for proactive maintenance, which leads to reduced downtime and enhanced safety for workers (Liu et al., 2024).

4.2 Adoption of Automated Ventilation Control Systems

The broad adoption of mine-specific automated control systems represents a significant development in ventilation technology (Levin and Semin, 2017). Sophisticated algorithms along with adaptive logic enable these systems to modify airflow in real-time according to operational demands, environmental shifts, and occupancy trends (Shriwas and Pritchard, 2020). Wireless communication technologies like ZigBee wireless sensor networks enable closed-loop control systems that automate secondary ventilation regulation under dynamic deep mine conditions (Di Nardo and Yu, 2021). Automation serves to improve safety levels while significantly cutting down electricity usage, thereby creating cost-effective and sustainable operations (Levin and Semin, 2017).

4.3 Application of IoT and Smart Digital Technologies

Mine ventilation network operations and monitoring have been transformed through IoT technology platforms (Zhang et al., 2023). IoT technologies connect sensors, actuators, and control units to enable complete real-time data collection and analysis for better decision support (Zhang et al., 2023). Operators who use smart digital systems can visualize ventilation performance and make predictions to optimize air delivery through extensive and complex networks at deep levels (Leonida, 2019). Such systems create safer work conditions and promote sustainable resource management (Leonida, 2019).

4.4 Energy-Efficient Ventilation Strategies

The deep mining sector recognizes the substantial energy requirements of traditional ventilation systems and actively focuses on creating and utilizing energy-efficient alternatives (Saleem, 2025). Prominent strategies include:

- VSD adjust fan operation to match actual ventilation requirements and achieve energy consumption cuts that can exceed 68% (Gonen, 2021; De Vilhena Costa and Da Silva, 2020).
- Advanced control frameworks enable ventilation-on-demand systems that direct airflow specifically to active work areas instead of continuously ventilating the whole mine (Zhang et al., 2023; De Vilhena Costa and Da Silva, 2020). The implementation of predictive optimization models based on mathematical and machine learning principles leads to improved energy savings and higher operational efficiency (Saleem, 2025).
- Distributed cooling solutions through modular cooling units target specific underground areas of high heat load to enhance both efficacy and cost-efficiency in air cooling systems.

The methods outlined here help to lower electricity usage while also making deep mining operations much more environmentally friendly through carbon footprint reduction (Saleem, 2025).

4.5 Enhanced Environmental Quality Monitoring

Next-generation ventilation systems rely heavily on innovative monitoring tools, which include rugged portable air quality monitors as well as comprehensive environmental sensor networks (De Cassia Pedrosa Santos et al., 2022). The monitoring devices perform ongoing assessments of temperature as well as humidity levels while measuring atmospheric pressure and gas concentrations and then send this data to central systems for adaptive control (De Cassia Pedrosa Santos et al., 2022). ZigBee-based wireless sensor networks stand out for their durability, minimal power usage, and expandability, which enables dependable environmental monitoring in mining operations (Di Nardo and Yu, 2021).

4.6 Advanced Simulation, Planning, and Decision-Support

Ventilation systems planning and optimization depend more and more on digital modeling and simulation tools. Today's CFD models and digital twin technologies give engineers the ability to model airflow patterns as well as heat distribution and contaminant movement across different operational conditions. The simulations deliver data-based knowledge necessary for selecting appropriate technologies as well as evaluating risks and making strategic investments in ventilation infrastructure. Multi-criteria decision-making frameworks help prioritize environmental improvement projects by optimizing safety outcomes and cost-effectiveness through coordinated efforts (Swanepoel et al., 2023).

4.7 Integration of Geospatial Information Systems (GIS)

Ventilation system management now utilizes GIS to achieve real-time mapping and visualization of airflow patterns and pressure levels along with ventilation device statuses in intricate mine layouts (Leonida, 2019). Mining operations depend on GIS platforms to maintain situational awareness while troubleshooting bottlenecks and planning network expansions or adjustments in ventilation systems (Leonida, 2019).

4.8 Eco-Friendly and Sustainable Ventilation Practices

Ventilation innovations focus on both environmental protection and sustainable development (Yang, Yao and Wang, 2022). Demand-driven ventilation systems and energy-efficient fan operations represent new control technologies that minimize energy costs and meet international environmental standards and legislative obligations (Yang, Yao and Wang, 2022). The intelligent systems maintain deep mining industry sustainability by integrating occupational health management with resource efficiency and environmental impact control (Yang, Yao and Wang, 2022).

4.9 Environmental and Safety Considerations in Underground Mine Ventilation

Efficient underground ventilation ensures air quality, thermal comfort, and environmental compliance while safeguarding worker health and mine sustainability. Key environmental priorities include managing hazardous gases such as CH_4, CO, and hydrogen sulfide (H_2S), controlling dust emissions, heat, and humidity, and treating exhaust air to prevent surface pollution (Vardhan, 2014; Srikanth, Supriya and Khader, 2023; Hartman et al., 1997; Gonen, 2018; Acuña and Allen, 2017). Ventilation systems mitigate explosion and toxicity risks by continuously diluting gases, removing particulates, and maintaining airflow adequacy (Srikanth, Supriya and Khader, 2023; Wang et al., 2024; Åstrand, 2016; Zhen, 2013). Safety designs integrate intelligent sensors, redundancy, and emergency reversal systems supported by CFD and disaster modeling for rapid response (Wan, 2024; Gillies, Wala and Wu, 2004; Ray et al., 2002). Compliance with international air quality and monitoring standards ensures ventilation reliability (Rhoton, 1980; Minin, Tauger and Minin, 2022). Best practices emphasize adaptive, data-driven systems like ventilation-on-demand and variable frequency drives, combined with predictive analytics, CFD optimization, and integrated dedusting to minimize energy consumption and enhance both safety and environmental performance (Wan, 2024; Farjow, Daoud and Fernando, 2011; Åstrand, Saarinen and Sander-Tavallaey, 2017; Aminossadati and Hooman, 2008; Sethi, 2015; Zhou et al., 2025).

5 COMPANIES EMPLOYING ROBOTICS IN UNDERGROUND COAL MINING

The following case studies from global mining companies demonstrate real-world implementation of the optimization and technological principles discussed earlier. The extreme heat and humidity in deep underground mines, along with dust accumulation and gas build-up, require complex airflow management, which means advanced ventilation systems are essential to protect miners and maintain operational productivity (Jacobs, Van Laar and Schutte, 2022). Substantial investments from major mining companies have led to the development of advanced ventilation systems that combine traditional large-scale fans with innovative technologies, including sensor-based monitoring and VoD systems, along with digital twins and battery-electric vehicles to tackle underground heat and emission challenges (Jacobs, Van Laar and Schutte, 2022; Trapani, 2019; Maestro Digital Mine, 2017; BioAge Group, LLC, 2022).

5.1 Glencore

Glencore leads the mining industry with its advanced ventilation systems used at the Kidd Mine, which operates as the deepest base metal mine around the globe, located nearly 3 kilometers beneath the Canadian surface (Maestro Digital Mine, 2017; Sithole, 2025). The Kidd Mine operates among the largest global vent fan systems, which work in conjunction with auxiliary fans and airflow monitoring stations to provide on-demand ventilation (Zadeh, 2025; Glencore Canada, 2023). The Maestro's Vigilante AQS™ Air Quality Stations and mine regulators measure airflow rate, direction, gas concentrations, and temperature to ensure miners operate within safe tolerances (Maestro Digital Mine, 2017). The implementation of these technologies delivers considerable energy savings that amount to 25,000 megawatt-hours each year, which equates to roughly $2 million USD annually (Maestro Digital Mine, 2017). Kidd Mine's ventilation system maintains airflow of over 1.2 million cubic feet every minute while incorporating digital twins to enhance operational efficiency (Zadeh, 2025).

Glencore's Onaping Depth Project features a fully battery-electric mining fleet that could decrease ventilation energy usage by 44% and cooling costs by 30% compared to diesel-based equipment, demonstrating how technological advancements can lessen ventilation requirements in deep mines (BioAge Group, LLC, 2022). Heavy equipment powered by batteries significantly lowers both emissions and heat production and cuts ventilation and air conditioning operating costs (BioAge Group, LLC, 2022).

5.2 AngloGold Ashanti and Harmony Gold

The deep mines operated by AngloGold Ashanti and Harmony Gold in South Africa include Mponeng, Savuka, TauTona, and Kusasalethu, which range in depth from about 3.7 kilometers to 4 kilometers (Sithole, 2025; Zadeh, 2025). The ventilation of these ultradeep mines presents unique challenges because rock temperatures reach extreme highs of up to 66°C at Mponeng's deepest points (Zadeh, 2025). The mining companies have installed systems that combine ventilation with refrigeration functions, and they also use VoD in relevant cases to manage these issues (Bruce, 2014). Obuasi Mine, operated by AngloGold Ashanti in Ghana, has developed a VoD system to replace traditional fans, which will facilitate area-specific ventilation control based on current demand and will reduce energy usage while extending equipment longevity (Bruce, 2014).

The Mponeng and TauTona mines maintain functional underground conditions through combined use of ice-slurry cooling technology alongside their ventilation systems (Zadeh, 2025). The implementation of these systems demonstrates both their ability to influence operational expenses and environmental sustainability while proving the critical need to align ventilation methods with changing mine designs (Jacobs, Van Laar and Schutte, 2022; Zadeh, 2025).

5.3 Codelco

El Teniente Mine, which functions as the world's biggest underground copper mine by volume, sits under the management of Codelco as Chile's state-owned copper producer and produces global copper output (Sithole, 2025; Zadeh, 2025). The underground network spanning more than 3,000 kilometers demands significant ventilation infrastructure with multiple large fans and ventilation raises plus scalable advanced control systems as the mine grows (Zadeh, 2025). The adoption of automation and digital monitoring at El Teniente has reinforced ventilation management efficiency with safe airflow and reduced energy consumption (Zadeh, 2025). The company receives recognition for its implementation of VoD systems, which utilize live sensor information to improve air distribution as a fundamental feature of modern deep mine ventilation design (Nyqvist and Serres, 2020).

5.4 BHP

The Australian Olympic Dam mine operated by BHP stands as one of the largest poly-metallic underground mines in the world while dealing with substantial heat and ventilation problems (Sithole, 2025; Zadeh, 2025). A highly engineered ventilation system integrates primary and auxiliary fans through performance-driven controls to support the mine's sublevel open stoping and block caving methods (Minetek Pty Ltd, n.d.). BHP stands out for its fleet transition to battery-electric vehicles, which results in decreased ventilation and cooling requirements because of lower heat production and reduced diesel emissions (Minetek Pty Ltd, n.d.). Minetek's ventilation systems, used by companies such as BHP, deploy performance-on-demand technologies to enhance airflow efficiency while reducing power consumption (Minetek Pty Ltd, n.d.).

5.5 Vale

Vale manages some of Brazil's deepest subterranean mines, which demand extensive ventilation together with refrigeration systems to handle problems that arise from depth, such as elevated rock temperatures and gas management (Johnston, 2024). The availability of explicit proprietary case studies about Vale mines is limited, but Brazilian deep-level mine ventilation now includes global best practices with VoD systems and cooling plants as well as calibrated digital twins reflecting international peer approaches (Jacobs, Van Laar and Schutte, 2022; Minetek Pty Ltd, 2024).

5.6 Rio Tinto

Rio Tinto operates major deep underground mines, including Oyu Tolgoi in Mongolia, along with large-scale operations at Bingham Canyon in the United States (Ashcroft, 2024). Large-scale mining operations maintain strong primary and secondary ventilation systems through the use of multiple shafts and high-capacity, energy-efficient fans (Minetek Pty Ltd, n.d.). Minetek’s solution endorsements state that Rio Tinto adopts cutting-edge airflow management systems that enable dynamic ventilation adjustments to match operational requirements and maintain safety standards (Minetek Pty Ltd, n.d.).

5.7 Agnico Eagle Mines

The Canadian LaRonde Mine, operated by Agnico Eagle Mines, uses sophisticated ventilation systems along with automated ore handling technology at depths surpassing 3 kilometers (Zadeh, 2025). Rail-Veyor technology deployment lowers underground diesel emissions and thereby reduces ventilation system strain (Zadeh, 2025). The company benefits from Minetek's custom fan system solutions that ensure steady airflow and improved energy efficiency (Minetek Pty Ltd, n.d.).

5.8 Additional Companies and Global Practices

Barrick Gold, Newmont, Sibanye-Stillwater, and Freeport-McMoRan have implemented top-tier ventilation systems in their deep mining operations through partnerships with renowned ventilation equipment suppliers (Minetek Pty Ltd, n.d.). The mining industry worldwide is adopting digital twins to enable operators to simulate and optimize ventilation networks before implementation, which reduces risks and operating costs, as demonstrated in gold mines located in South Africa (Jacobs, Van Laar and Schutte, 2022.

Table 3 Companies and Ventilation Implementation

Company	Representative Mine(s)	Key Ventilation Features	Technological Innovations
Glencore	Kidd Mine, Onaping Depth	Large vent fans, auxiliary fans, VoD, air quality sensors	Digital twins, battery-electric fleet
AngloGold Ashanti	Mponeng, Savuka, TauTona	VoD, refrigeration, ice-slurry systems	Sensor-based monitoring, advanced cooling
Harmony Gold	Kusasalethu, Mponeng (since 2020)	VoD, conventional and digital integration	Area-based ventilation control
Codelco	El Teniente	Large fans, ventilation raises, automation, VoD	Real-time sensor networks
BHP	Olympic Dam, Escondida	Engineered duct and fan systems, VoD	Battery-electric fleet integration
Rio Tinto	Oyu Tolgoi, Bingham Canyon	Multiple ventilation shafts, dynamic controls	Endorsed third-party airflow management
Vale	Various, Brazil	Large-scale fans, refrigeration, simulation tools	VoD, digital planning
Agnico Eagle Mines	LaRonde	Automated ore handling, optimized fan systems	Rail-Veyor, Minetek fan technologies
Others (Barrick, Newmont, etc.)	Multiple deep mines	International best practice adoption	Sensor networks, modular fans, digital twins

6 CHALLENGES AND FUTURE SCOPE IN IN VENTILATION SYSTEMS FOR DEEP UNDERGROUND MINES

The optimization and innovation trends discussed above highlight both the progress achieved and the emerging challenges faced by the deep mining industry. The basic function of ventilation systems in deep underground mining operations is to ensure a safe and productive environment, but these systems face growing difficulties as mining depths extend (Bojilov, Hadjiev and Shoushoulov, 1999). Effective ventilation removes harmful gases and controls dust while reducing heat and delivering safe, breathable air, which protects miners and maintains operational efficiency (Gonen, 2018). Deep mines create unique environmental conditions that require specialized solutions, which result in ventilation planning becoming a continuously developing field through innovative techniques and technological designs.

6.1 Challenged

• Heat and Humidity Management: The primary challenge that emerges as mining operations extend into deeper levels involves controlling temperature and humidity because of increased geothermal gradients and heat generated by equipment. When mines reach specific critical depths, natural ventilation systems fail to provide sufficient cooling, which necessitates the installation of additional cooling systems, such as centralized or spot cooling, to maintain safe temperatures for miners and support their productivity (Kamyar et al., 2016). The requirement to address both air auto-compression and heat generation from geological layers increases the necessity for energy-demanding refrigeration systems (Thibodeau and Jodouin, 2014).

• Control of Harmful Gas Emissions: CH_4 release from diesel equipment creates ongoing threats of toxic exposure and explosions when ventilation fails to sufficiently remove or dilute these gases (Imgrund, Bischoff and Spürk, 2019). Mining operations at greater depths present operational complexities through expanded working faces and larger equipment inventories, which boost emission volume and challenge air supply delivery to essential mine locations (Gonen, 2018; Grishin, Zaitsev and Kuzminykh, 2020). When airflow distribution fails or airflow levels remain insufficient, it results in gas stratification involving CH_4 along with the accumulation of exhaust elements such as CO and nitrogen oxides (NOx), which create severe risks to workers (Grishin, Zaitsev and Kuzminykh, 2020).

• Aerodynamic Resistance and Network Complexity: As mine depth increases, ventilation routes extend and become more complex, which leads to higher aerodynamic resistance and energy usage as well as diminished effectiveness in the ventilation system (Bojilov, Hadjiev and Shoushoulov, 1999). Mine layouts aimed at maintaining geomechanical stability tend to have smaller cross-sectional areas, which lead to increased resistance and restricted airflow, thereby complicating the process of full mine ventilation (Thibodeau and Jodouin, 2014). Notably, balancing ventilation requirements with geomechanical constraints presents an ongoing struggle: Large conduits improve airflow but jeopardize rock stability, while small openings ensure geotechnical safety despite their limitation on airflow (Thibodeau and Jodouin, 2014).

• Stability and Environmental Fluctuations: In deep mines, airflow direction and volume become unpredictable when natural wind pressure and barometric conditions change (Wang et al., 2022). When ventilation systems fail to monitor or respond effectively to airflow fluctuations, they can result in dangerous gas overruns and poor air quality, which highlights the critical need for adaptive and strong ventilation controls (Wang et al., 2022).

• High Energy Consumption and Cost: Ventilation ranks as one of the top energy-consuming operations in underground mining because it typically uses 30–50% of the mine's total electrical power (Pandey, Mischo and Drebenstedt, 2015; De Souza, 2018).

Substantial power requirements for large main and auxiliary fans that push air through complex high-resistance networks result in increased operational costs and carbon emissions (Papar et al., 1999). The financial strain becomes more severe when mines extend deeper and ventilation demands increase (Gonen, 2018).

• Maintenance and System Efficiency: Frequent problems such as leakage through stoppings and doors and inefficient fan operation in addition to outdated infrastructure without variable controls generate poor volumetric efficiency, which results in only a small portion of ventilated air being effectively used (Hairfield and Stinnette, 2009). System performance metrics demonstrate that numerous systems operate at efficiencies lower than 65%, which presents major potential for enhancements and waste minimization (De Souza, 2018).

• Safety, Health, and Emergency Preparedness: Deep mines experience heightened safety concerns because poor ventilation systems can trigger hazardous events like fires and explosions and result in gas poisoning and heat-related illnesses (Grishin, Zaitsev and Kuzminykh, 2020; Stewart, 2021). Real-time monitoring and fast system responses are essential during emergencies, yet many current models lack the ability for immediate hazard prediction or mitigation (Stewart, 2021).

6.2 Future Scope

• Advanced Monitoring and Integrated Control: The development of IoT-based monitoring systems that provide real-time evaluation of environmental factors such as gas levels, temperature, humidity, and airflow represents a key area of progress (Zhang et al., 2023). The implementation of wireless sensor networks with ZigBee technology enables ventilation control systems to dynamically adjust airflow in response to real-time underground conditions (Di Nardo and Yu, 2021).

• VoD and Automation: VoD systems stand out as a groundbreaking innovation through their automatic modulation of fans and additional systems to provide necessary airflow exactly where and when required (Pandey, Mischo and Drebenstedt, 2015). The strategy achieves energy reduction by saving up to 50% and improves carbon management through reduced ventilation during inactive periods and in vacant areas (Gonen, 2021; Farjow, Daoud and Fernando, 2011). Remote diagnostic and control systems that operate fans benefit from VoD support through the use of advanced communications infrastructure (Farjow, Daoud and Fernando, 2011).

• Energy Efficiency Optimization: Advanced mathematical models such as the Hardy Cross method combined with machine learning algorithms like gradient boosting enable optimal fan positioning and pressure management to minimize power consumption and enhance airflow distribution (Saleem, 2025). VSD installed on auxiliary fans provide uninterrupted airflow management in accordance with demand levels while boosting system efficiency (Gonen, 2021). System-wide energy audits and equipment upgrades generate non-energy advantages such as extended equipment lifespan and decreased maintenance costs (Papar et al., 1999).

• Enhanced Simulation and Predictive Modeling: The field of modern ventilation design depends more than ever on advanced simulation tools, including CFD-based software and transient analysis models, to achieve accurate predictions of airflow behavior along with thermal loading and contaminant movement (Fair et al., 2021). Mine engineers use these tools to predict how changing environmental conditions or emergency situations like fires or gas leaks will impact operations while enabling safer mine design and proactive responses (Imgrund, Bischoff and Spürk, 2019; Stewart, 2021).

• Cooling Technologies and Renewable Integration: The next generation systems will merge ventilation with sophisticated cooling technologies that surpass conventional refrigeration by including targeted cooling methods and renewable energy solutions like organic Rankine cycle systems or liquid air energy storage (Cluff, Kennedy and Foster, 2014). The integration system delivers two essential advantages by managing temperature and reducing energy costs in deep and ultra-deep mining operations (Cluff, Kennedy and Foster, 2014).

• Addressing Environmental and Geomechanical Synergism: New methods are being developed to solve the conflicting demands between proper ventilation and maintaining geomechanical stability (Thibodeau and Jodouin, 2014). Optimized mine layouts, along with strategic infrastructure planning and coordinated planning processes that address both air delivery and long-term rock support, make up essential components.

• Expansion of Real-Time Response and Emergency Management: Real-time or near-real-time simulation capabilities in dynamic ventilation modeling enable proactive responses to hazardous events through improved prediction capabilities (Stewart, 2021). The addition of these modeling functions to operational processes ensures better protection in standard operations as well as emergency situations.

• Toward Smart, Sustainable Mining: Intelligent and adaptive ventilation systems of the future will operate based on extensive data analysis while ensuring full integration with mine-wide environmental and safety management systems (Zhang et al., 2023). The development of next-generation ventilation control systems in mines will be based on system interoperability along with advanced analytics and self-powered or low-maintenance sensors together with cyber-physical security to achieve increased sustainability and safety as well as improved resilience (Di Nardo and Yu, 2021).

7 CONCLUSION

This paper, based on an extensive literature review, synthesizes current approaches to optimizing ventilation systems for deep underground mines. The paper on the design and optimization of ventilation systems for deep underground mines highlights several critical aspects that are essential for improving safety, efficiency, and sustainability in mining operations. Ventilation system optimization remains essential to achieve proper airflow while diluting dangerous gases and reducing energy use. Mining operations face greater challenges to environmental conditions when they extend deeper underground. Utilizing advanced technologies, including GIS, significantly improves ventilation management techniques. Real-time mapping and monitoring systems enable essential troubleshooting and planning of adjustments for complex mine layouts. Modern ventilation strategies aim to achieve operational efficiency while also putting sustainability at the forefront of their objectives. Demand-driven ventilation systems and energy-efficient fan operations help minimize energy expenses while meeting international environmental standards. Multiple real-world examples show that optimization strategies deliver measurable results through significant energy savings and better adherence to health and safety standards. Practical applications demonstrate how adaptive controls, along with simulation-based design improvements, successfully resolve specific ventilation problems at mining sites. The reviewed studies collectively demonstrate that ongoing research and technological development are necessary to meet evolving ventilation demands in deep mining operations. The literature establishes that effective management of ventilation systems is a vital component of safe and efficient mine operation, influencing safety standards, productivity, and environmental outcomes. The ongoing development of airflow planning techniques coupled with the addition of predictive maintenance capabilities will boost the durability and performance of ventilation systems. The paper concludes that deep mining industries need to adopt new technologies and strategies to ensure their long-term sustainability.

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Original scientific paper

OPTIMIZATION OF OIL PRODUCTION BY USING SUCKER ROD PUMPS BY MAINTAINING OPTIMAL SYSTEM BALANCE

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Abstract: This paper explores the optimization of oil production by using sucker rod pumps while maintaining optimal system balance. Loss of efficiency due to unbalanced pump units and increased energy requirements are the key challenges in the exploitation of oil wells. In order to overcome these problems, an intelligent monitoring system has been explored and it integrates sensors, SCADA platform and predictive algorithms for real-time performance monitoring. The research has been conducted on five oil wells, where the key parameters, electric current, motor power and gearbox torque have been analyzed – before and after balancing the system. The results show a reduction in peak current and motor power, as well as the elimination of negative torque, thus increasing the efficiency and reliability of the equipment. Based on the calculation of electricity consumption, savings of 8% to 14% have been recorded, with an average value of 11%. In addition to energy efficiency, optimal balancing contributes to extending the service life of the gearbox and reducing the number of production downtime. The obtained results confirm that the combination of CBM approach and intelligent remote monitoring is a reliable basis for improving the exploitation of oil by using sucker rod pumps. This approach contributes to reducing operating costs, preserving equipment and achieving sustainable development goals in the oil industry.

Keywords: Optimization, Oil Production, Predictive, Sucker Rod, System Balanced

1 INTRODUCTION

After the drop in a formation pressure in the oil-producing wells by using reservoir energy, the mechanical method of exploitation (gas lift, sucker rod pump, electric submersible pump, hydraulic pump) is chosen in order to ensure the extension of the production life and increase the final utilization. The choice of method depends on the

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characteristics of the reservoir, well and fluid being produced. The oldest method of applying sucker rod pumps. The number of wells in the world that produce oil by using this method can only be assumed and is 21%, while their share in oil production is 7%. Given their large share in oil production, the main goal of the engineers is to safely manage the production of wells with the least amount of operating costs, downtime and failures of the equipment (Kis, 2021).

(Bode, 2019) states that such systems have shortcomings in terms of loss of efficiency due to poor system balance, paraffinization impact and reactive response due to the distance of oil fields. Precisely because of this loss of efficiency, it is proposed to introduce an intelligent system for monitoring the operation of sucker rod pumps, which consists of three levels: conventional pump unit with sensors, RMS level with industrial computers for collecting and sending data through the MODBUS protocol and from the level of the centralized control station (Aliev et al., 2018).

This paper describes the method of maintenance according to the state or predictive maintenance of the system in order to reduce the costs of oil exploitation, to reduce the consumption of electricity, which is directly related to the reduction of the negative impact on the environment, as well as the extension of the service life of the equipment.

2 METHODOLOGY

We live in a time when a new generation of industrial automation, intelligent production and advanced technologies is emerging, leading to Industry 4.0 and digital business.

Predictive maintenance of assets in production plants is a key component of the concept of e-production. Predictive maintenance systems, known as e-maintenance, allow production and operating systems almost zero frequency of downtime, through the use and integration of real-time monitoring (Wu et al., 2016). These systems are capable of comparing product performance through globally networked monitoring systems, enabling a shift of focus from fault detection and diagnostics towards predicting and forecasting degradation.

Remote monitoring and evaluation of the system performances in real time requires the integration of various technologies, including sensor devices, wireless communication, virtual integration and interface platforms (Gregor et al., 2016).

2.1 Maintenance method according to the condition

This paper is based on the application of modern technologies and methods of monitoring the parameters and their use within the maintenance of the oil production system by sucker rod pumps. The modern concept that deals with the detailed analysis of all aspects of maintenance is called the CBM concept, i.e. Condition-Based

Maintenance. In order to implement this concept in a thorough and quality manner, it is necessary to have the appropriate equipment within the maintenance system, which is the basic form of diagnostics, known as "Condition Monitoring".

This research paper will show all the measurements that have been used as the basis for the analysis, on the basis of which the appropriate conclusions and recommended steps for the improvement of production were made. These improvements are directly reflected in the more reliable operation of the oil production system, and accordingly in the increase in the efficiency of the systems.

When collecting data for the research, devices (sensors) have been used to constantly monitor the behavior of the parameters in real time, including the frequency controller for obtaining data on the operation of the electromotor for the analysis of the dependence of electricity consumption on the amount of fluid (oil) produced. In addition to the aforementioned sensors, data from the measuring gauge have been used to analyze the impact of the pump unit on the motor frequency, i.e. the impact of the system imbalance on the generation of the reactive motor power.

Based on all the collected data, the elimination of the causes of the problems that have affected the potential downtime as well as the reduction of the efficiency of the system has been initiated and the achieved results have been determined.

Traditional maintenance methods have evolved into modern approaches, such as condition-based maintenance (CBM). CBM makes maintenance decisions based on the current state of the machine, which is monitored through a measurement system (Jardine et al., 2006). This approach reduces the frequency of maintenance, with the performance of interventions only when really needed, which saves costs and improves consistency (Marseguerra et al., 2002). With the advent of the fourth industrial revolution and the advancement of computer and visualization technologies, a new era has emerged in the field of maintenance, known as prescriptive maintenance (Matyas et al., 2017). This concept goes beyond just predicting failures and focuses on proactive and smart maintenance planning, enabling machines to make their own decisions and guide users towards solutions (Lee et al., 2020).

The CBM concept consists of three key steps (Jardine et al., 2006; Lee et al., 2020) and they are:

1. Collecting relevant data to create a successful system,
2. Data processing (management of the received information), processing the signals important for understanding the problems with the system,
3. Making a decision on the manner of maintenance based on the collected data, proposing an effective maintenance policy

Figure 1. shows the three basic steps in the CBM concept, as defined by (Lee et al., 2020).

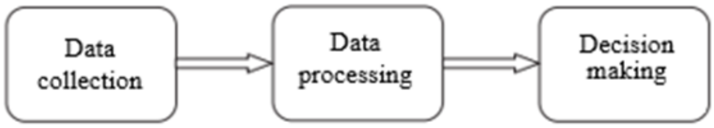


Figure 1 Three steps of the CMB concept

2.2 Basics of the oil production system by using sucker rod pumps

The oil production system with sucker rod pumps consists of a surface unit, a series of sucker rods and a sucker rod pump. The surface unit, called the pump unit, is the drive of the system. **Figure 2.** shows the scheme of the conventional design of the pump unit (Langbauer et al., 2021).

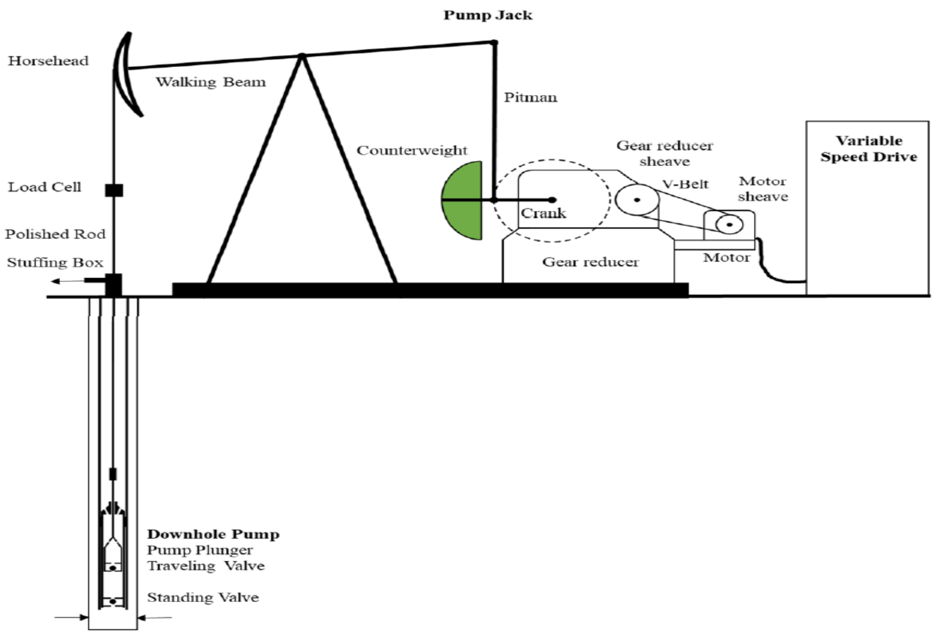


Figure 2. Oil production system by using sucker rod pumps

The first part of the pump unit reduces the rotation speed, while the second part transforms the rotation into translation. The pulley of the electromotor is driven by V-belt, which drives the pulley of the gearbox and is the first stage of speed reduction. The gearbox pulley is installed on the inlet shaft of the two-stage gearbox, which further reduces the rotation speed. A final speed is achieved on the output shaft of the gearbox.

This transmission system usually reduces the motor speed from 1,000 rpm by a factor of about 150 to 200. Finally, the system speed (number of strokes) in the range between 3 and 15 rpm is reached. The crankshafts carry a counterweight, which balances the weight of the rods, and are connected to one end of the balance beam. At the other end of the balance beam, a horse head is placed. The horse head hangers carry a polished rod, which passes through the sealing head and the blowout preventer. The polished rod is connected to a series of sucker rods, which transmits the movement of the pump unit to the pump rod (Langbauer et al., 2021).

2.3 Remote monitoring of the system operating parameters

In practice, there are several alternative methods that can be used to detect the degree of balance, such as time ratios, peak current, total power consumption and peak torque between downward and upward movement of a polished rod. These methods have a high practical value, but the labor costs are high without help of the automatic system for assessing the degree of balance.

The remote monitoring platform consists of two parts, including the database and the web server, as well as the remote monitoring unit. The database and web server receive real-time status data sent from different oilfields via GPRS (General Packet Radio Service), store it in the database and deliver web pages to remote terminals. The remote monitoring unit allows customers to monitor the operating states of the pump units by using a browser on a computer and respond to abnormal situations in a timely manner, as described in the relevant paper (Lv et al., 2016).

On Figure 3. a scheme of the remote monitoring system of well operation is presented.

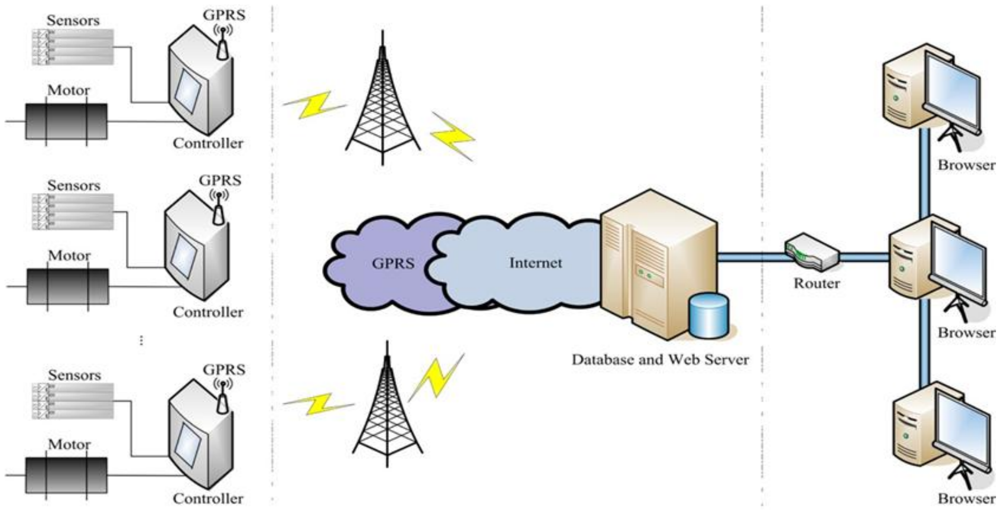


Figure 3. Remote monitoring system (Lv et al., 2016)

2.4 System balance

The best method that the operator can use to balance the net peak torque on the pump unit gearbox is to simultaneously apply power and mechanical methods to determine the existing net torque of the gearbox. When analyzing the net torque graph, the power torque overlaps with the net torque of the gearbox obtained by the mechanical gauge, which allows easy visual reassessment of the graph and identification of discrepancies. The dynamogram and power data can be further analyzed to determine the current net torque of the gearbox. This torque is calculated for upward and downward movement conditions, and then the recommended distance for the movement of the counterweights to balance the unit is displayed. Balancing the pump unit is facilitated by using this combination of motor power measurement and dynamogram. If the net torque of the gearbox on the pump unit is kept in balance, then the peak torque on the motor and gearbox is lower, the peak power supplied by the motor is lower, and the peak current drawn by the motor is reduced, thus reducing energy costs and increasing the service life of the equipment (Rowlan et al., 2005).

2.4.1 Net torque

In general, three types of torque can be distinguished on the pump unit gearboxes (Gibbs, 1992):

1. The torque of the rod is the result of the load of the polished rod and can be calculated based on the kinematic parameters of the unit.
2. The torque of the counterweight is necessary to move the counterweights. It has a sinusoidal shape relative to the angle of the crankshaft in mechanisms that use rotary counterweights.
3. Inertial torque is the energy stored in parts of the pump unit, which is used to accelerate or decelerate, whereby it is released during operation. This torque can be significant if the variation in crankshaft speed is significant.

The net torque on the speed gearbox is the sum of the above-stated components. This is the torque that must be provided by the power input from the main drive. Detailed methods of calculating the net torque components of the crankshaft are presented below (Takacs & Kis, 2021).

On Figure 4. The torques being the components of the net torque as a function of time for one pumping cycle are presented (Kis, 2021).

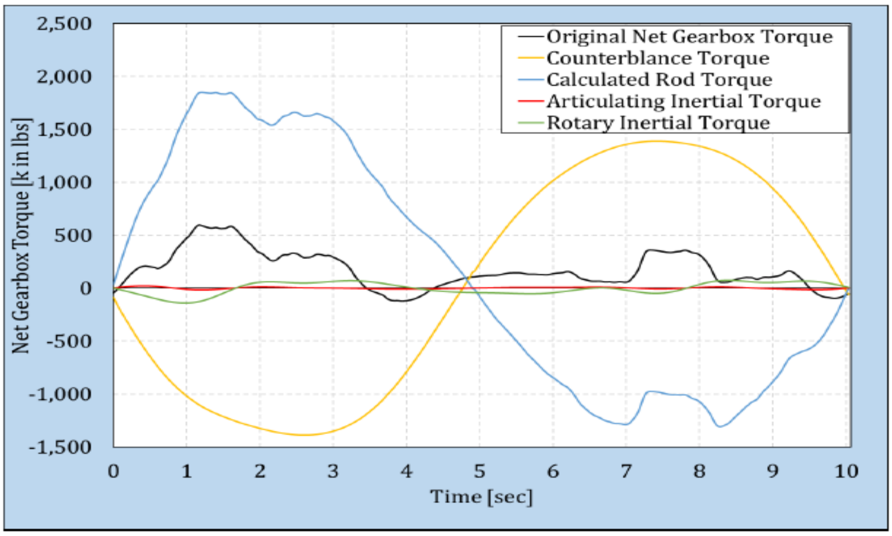


Figure 4. The components of the net torque as a function of time for one pumping cycle

2.4.2 System balance

For each complete stroke, the net torque of the load on the gearbox is cyclic, usually with two maximum and two minimum peaks. The upward peaks occur during the upward and downward movement of the polished rod, and the minimum peaks occur in the upper and lower position of the polished rod. For balanced operation, the magnitude of the peaks should be approximately equal. The pump unit manufacturers use different types of balancing and mechanical characteristics to reduce the peak torque of the gearbox and mitigate the cyclic impacts of the load.

The gearbox is said to be under-balanced if the upward peak is higher, and the gearbox is said to be over-balanced or too heavy if the downward peak is higher. Since in the rotating system the torque and power are directly related, the above-stated statements can be equally applied to the cyclic nature of the motor power developed during the complete stroke of the pump unit. Figure 5. illustrates these concepts and definitions for the torque (Nm) or power (kW) markings of the motor (McCoy et al., 1999). If the net torque of the gearbox is kept in balance, then the peak torque imposed on the motor, the peak power supplied by the motor and the peak current drawn by the motor are reduced, thus reducing energy costs (Rowlan et al., 2005).

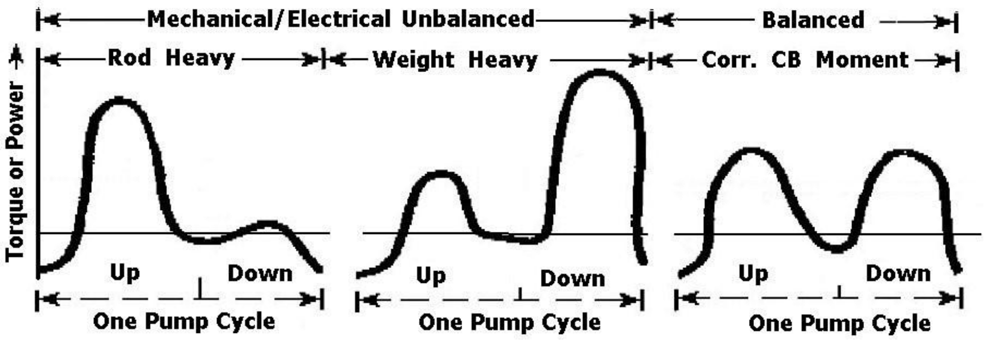


Figure 5. Torque (Nm) or power (kW) for unbalanced/balanced systems

Figure 6. shows that the torque, calculated from the electrical power on the motor, behaves in almost the same way as the net mechanical torque on the gearbox, calculated from the load measurement on the polished rod. Both the motor output torque and the gearbox torque have a peak (maximum) and a drop (minimum) on the part of the pump cycle, when moving upward and downward. The power and mechanical torque data show that this crankshaft balanced pump unit is too heavy (over-balanced) and the counterweights should be moved inwards from the end of the crankshaft to balance the torque peaks. Also, notice that when the gearbox shows a negative mechanical torque, this also happens with the motor. The negative torque of the motor is the result of a combination of the torque of various moving elements (including crankshafts, weights, beam and rod loads) that drive the motor over its synchronous speed where it operates in the "regenerative power" mode during that part of the stroke (Rowlan et al., 2005).

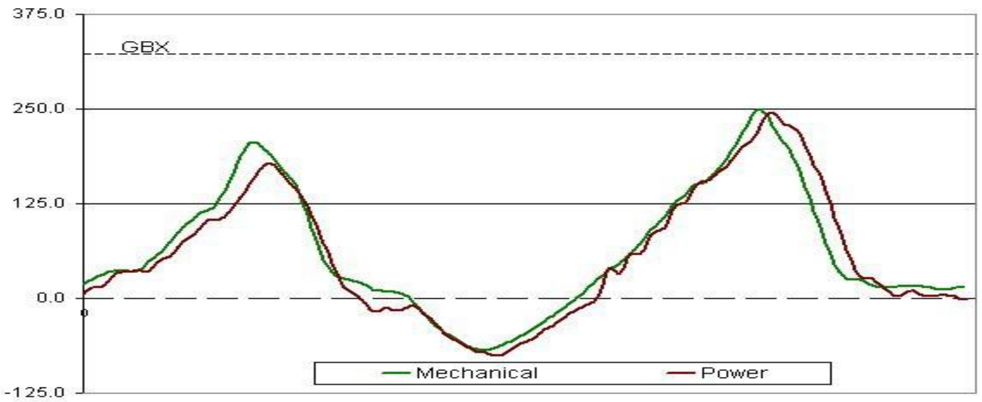


Figure 6. Comparison of the torque diagram from the dynamogram and motor power in one pumping cycle

2.4.3 Gearbox service life

The most important parameter that determines the service life of the gearbox is the ratio between the nominal torque of the unit and the torque load during its operation. Figure 7. illustrates the effect of the overload, showing that only 10% of the increased torsional load relative to the nominal value can reduce the service life of the gear by half, and 20% of the overload can result in only one fifth of the service life specified by the manufacturer (Kis, 2021).

A common problem due to overload is pitting corrosion – a type of the surface fatigue – when the stress on the surface of the gear teeth exceeds the limit of the periodic load material. These surface cavities can lead to gear teeth failures at overloaded gearboxes, in accordance with ANSI/AGMA 110.04, Gear Tooth Failure Mode Nomenclature (Elliott et al., 2018). Therefore, achieving the optimal torque load improves the service life of the most expensive part of the sucker rod pump installation. This can be achieved by applying the appropriate balance of the pump unit.

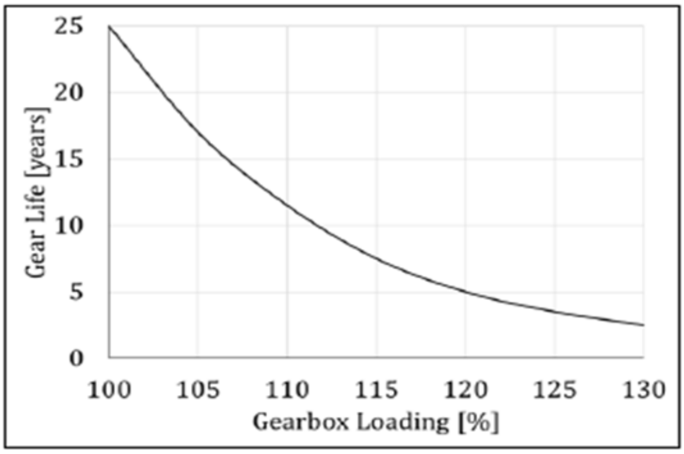


Figure 7. Dependence f the gearbox service life and operational overload (Clegg & Lake, 2007; Kis, 2021)

2.4.4 Optimal balancing benefit

Proper balancing of the pump unit gearboxes brings a number of direct and indirect benefits, which are summarized below (Podio et al., 2001; Rowlan et al., 2005; McCoy et al., 1999):

The torque size required for the gearbox can be significantly reduced compared to the unaccounted state, thanks to lower peak torque. The required electromotors can have a lower nominal power due to smaller changes of the load and a lower load coefficient.

The service life of the equipment, especially the gearbox, may be extended due to a reduced number of torque fluctuations. Operating costs are reduced due to lower energy costs, resulting from the reduced energy consumption for heating the motor, as well as lower maintenance and replacement costs due to the balanced operation of the gearbox.

3 RESULTS AND DISCUSSION

For the purpose of analyzing the impact of the optimal system balance, the conventional system for the mechanical method of oil exploitation has been used with sucker rod pumps with an integrated system of an intelligent control and real-time data transfer. Figure 8. shows one such system.

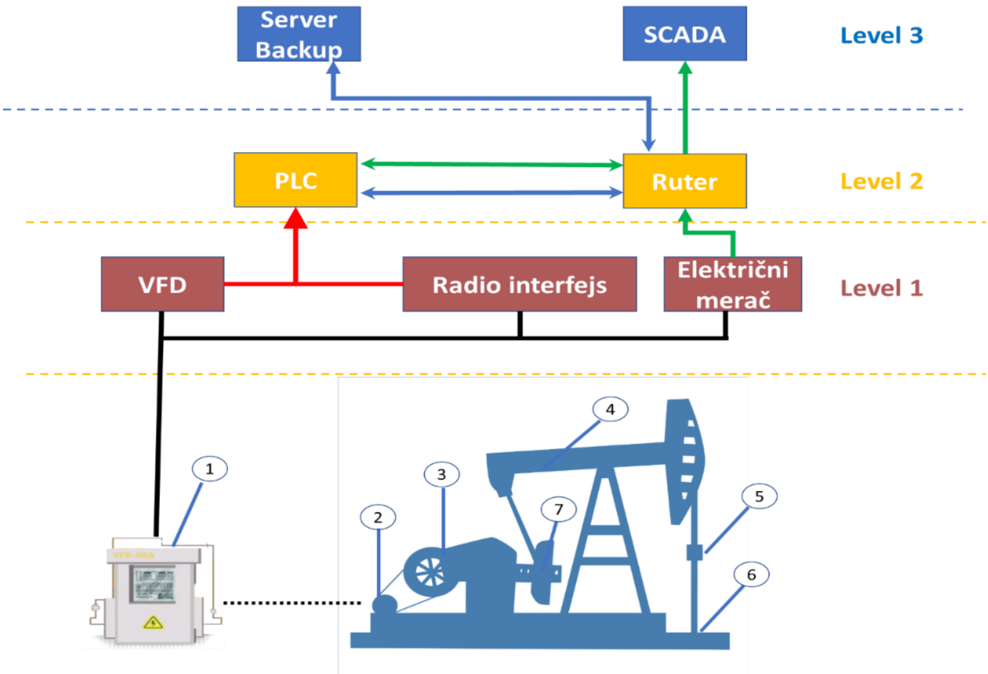


Figure 8. Data transfer from the well to the user (SCADA), (1-Intelligent Control Station (ISU), 2-electromotor, 3-gearbox, 4-balance beam, 5-dynamograph, 6-sonologist, 7-weights)

As highlighted in the theoretical research of this paper, the pump unit balance is monitored through a combination of motor power parameters (kW) and data from the dynamogram (load in N). If the net torque of the gearbox on the pump unit is kept in balance, then the peak torque on the motor and gearbox is lower, the peak power supplied by the motor is lower, and the peak current drawn by the motor is reduced, thus reducing energy costs and increasing the service life of the equipment. These are the conditions for optimizing the cost of oil production with sucker rod pumps.

The implementation of an intelligent control system provides straightforward information on the need to balance the system. The intelligent management system monitors the mentioned operating parameters and, through software solutions, reports the problem to the monitoring specialist when the torque reaches the set limit value. Considering that the torque is directly proportional to the current power and motor power, when reaching the maximum value of peak power and peak current, the ISU activates an alarm that the torque set value has been reached. At that point, the monitoring specialist has sufficient time to issue a request to balance the pump unit and bring the system into balance. In addition, by monitoring the growth trend of the peak current and peak motor power, the specialist can predict before the alarm when balancing will be required. Timely balancing saves energy, protects equipment from breakage and optimizes oil production.

The research has been conducted on five oil wells and similar results have been obtained on each of the wells. Predictive maintenance has saved energy, protected equipment from malfunction and reduced the number of production downtime to zero.

It should also be noted that the quality balance annuls the reactive motor power and protects the power supply system from damage and reduces the cost of charging for energy returned to the power supply network. The research will show the impact of a good balance on the reduction of the reactive energy of the electromotor.

The visualization of the parameters from the electric gauge has been done through the AVEVA platform and allows the specialists to notice the problem of imbalance and react to the problem in a timely manner by issuing a request for balancing the pump unit.

Figure 9. shows the parameters: frequency F(Hz), current I(A) and power P(kW) in real time, before balancing and after balancing the pump unit.

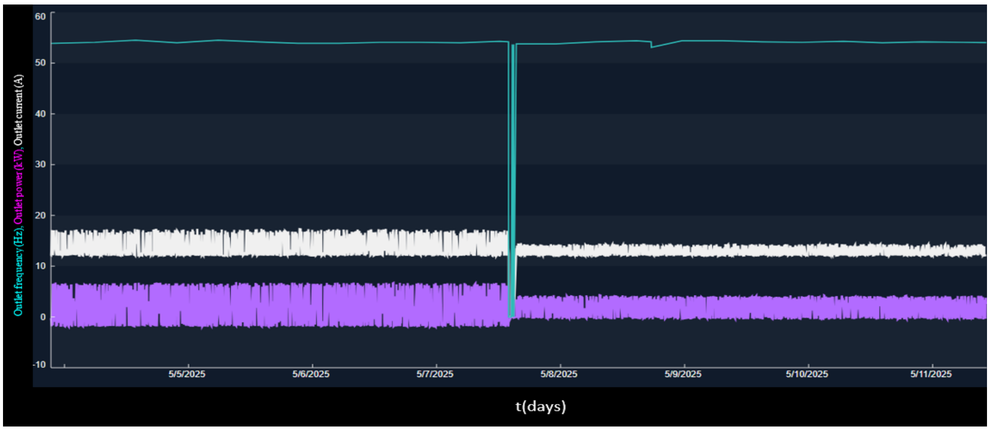


Figure 9. Display of operating parameters of the electric motor in real time - frequency F(Hz), current I(A) and power P(kW) in real time, before balancing and after balancing the pump unit

Considering that the torque is in direct proportional dependence on the current (motor power), as defined in the theoretical part of the research, the torque of the motor, i.e. the load on the gearbox is reduced and the negative torque value is neutralized.

Figure 10. Shows the motor torque before and after balancing the pump unit.

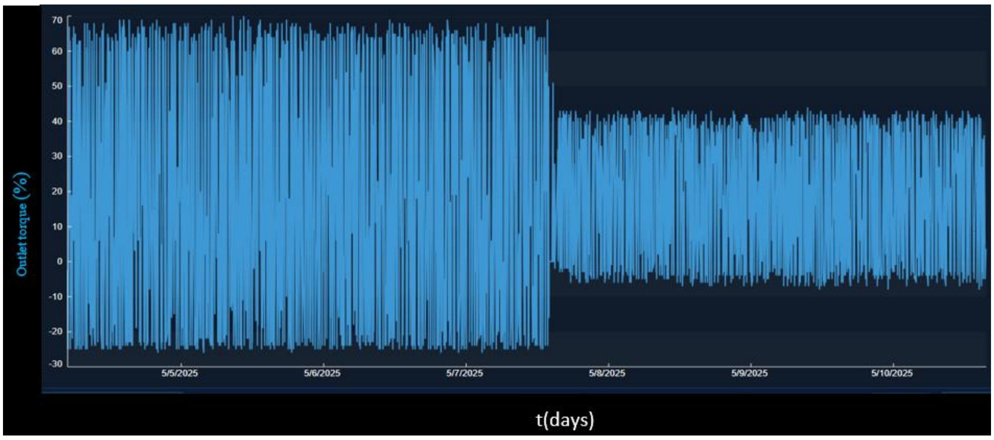


Figure 10. Diagram of the motor torque before and after balancing the pump unit

The research has been conducted on five wells (K-001, K-002, K-003, K-004 and K-005) where increase in peak currents, in peak motor power and in torque has been determined by remote monitoring. Special emphasis is placed on the reduction of electricity consumption after balancing, as well as on the reduction of the torque that impacts the extension of the service life of the surface equipment, especially the gearbox.

In Figures 11. and 12, the dynamograms before and after balancing are shown. It can be observed that the imbalance of the system does not affect the increase or decrease of the maximum and minimum load. Given that the oil production system uses a frequency regulator, the pumping speed is constant. To maintain a constant speed, electrical parameters such as current (I) and the power (P) consumed to drive the motor are adjusted.

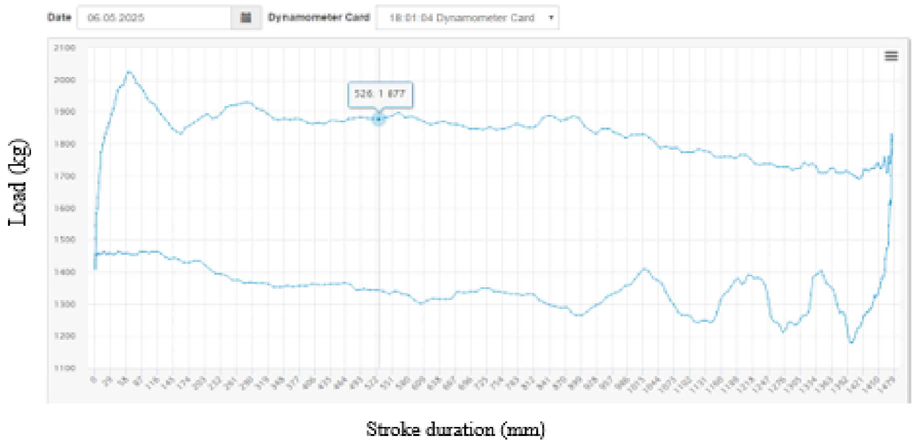


Figure 11. The dynamogram before balancing the system

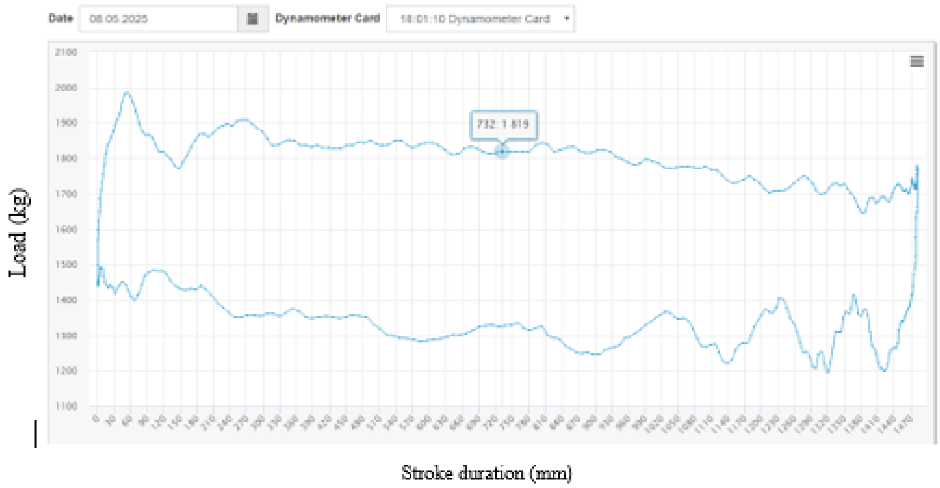


Figure 12. The dynamogram after balancing the system

In Table 1 the wells are presented along with the key operational parameters and installed pumps.

Table 1 The wells with the key operational parameters and installed pumps

Well	Pump	Installation depth (m)	Percentage of water (%)	Daily fluid production (m3)	Stroke duration (mm)	Number of strokes (o/min)
K-001	25-175-RHAM-12-3-2-0	1205.52	92	22	2151	4.6
K-002	25-175-RHAM-13-3-1-0	1192.46	87	12	1600	3.9
K-003	25-175-RHAM-13-4-1-0	900.32	91	17	1565	5.3
K-004	25-175-RHAM-12-3-2-0	1560.21	67	13	1470	4.3
K-005	25-175-RHAM-13-3-1-0	1599.23	58	12	1569	4

During the research, the analysis has been performed by using historical data from the SCADA platform. The analysis has been performed by monitoring the current before and after balancing, and the difference of the mean value of the current has been taken into account for the calculation of the consumed electricity before and after balancing.

3.1 Mathematical calculation of electrical energy consumption

In the oil extraction system using sucker rod pumps, an asynchronous motor is used as the driver. The asynchronous motor is connected to the electrical grid from the stator side, from which it draws electrical power P_1 (kW) (consumed power). The rotor is mechanically coupled to a reducer, which transmits useful mechanical power P (kW). The difference between the consumed electrical power P1 and the useful mechanical power P is equal to the total losses occurring in the motor, which consist of electrical, magnetic, and mechanical losses, specifically losses in copper, losses in iron, and losses due to friction and ventilation (Vukić et al., 2011).

The electrical power P is the rate of change of electrical energy W, which varies with time t. The unit of measurement is the watt (W).

$$P = \frac{W}{t} = U \cdot I \tag{1}$$

Where:

- W - electrical energy (J),
- t - time (s),
- U - voltage (V), and

- I - current (A).

Depending on the total load of the oil production system using piston pumps, a certain total power is consumed, referred to as the apparent power of the consumer S (VA), which is represented by:

$$S = U \cdot I \tag{2}$$

Where:

- S - apparent power (VA) and I - current (A).

The apparent power consists of two different components:

1. Active power P (kW), which represents the useful component, and
2. Reactive power Q (VAr), which usually represents system losses.

The power triangle illustrates the relationship between useful power P, reactive power Q, and apparent power S as a function of the angle of the power components φ, as shown in Figure 13.

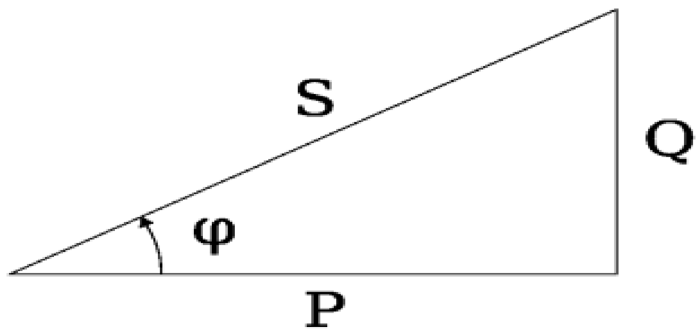


Figure 13. Power triangle (Vincetić, 2022)

The apparent power can be calculated using a triangle according to the equation (3):

$$S = \sqrt{P^2 + Q^2} \tag{3}$$

Where:

- P - active power (W), and
- Q - reactive power (VAr).

The power factor cosφ is defined by the ratio of active (P) and apparent (S) power according to equation (4):

$$cos\varphi = \frac{P}{S} \tag{4}$$

Active power P is the useful power that transfers electricity from source to consumer. The unit of measurement of manpower is watt (W). It performs useful work and is converted into another useful form of energy. Also, the workforce depends on the work of consumers and power factors. The working power of P is equal to the product of the effective value of current and voltage at the input connections and the power factor of cosφ (for monphase engines) according formula (5):

$$P = U \cdot I \cdot cos\varphi \tag{5}$$

That is:

$$P = \sqrt{3} \cdot U \cdot I \cdot cos\varphi \tag{6}$$

for three-phase engines acoording formula (6).

Where:

- cosφ - power factor defined by the phase angle φ, which in passive networks can be $\pi/2 < \varphi < \pi/2$, so $0 \leq cos\varphi \leq 1$. If φ=0 i cos φ=1, there are no reactive elements in the system then.

The reactive power of Q is equal to the product of the effective values of the current, voltage and sinuses of the phase angle phi (for monophasic engines) according to equation (7):

$$Q = \sqrt{3} \cdot U \cdot I \cdot sin\varphi \tag{7}$$

That is:

$$Q = \sqrt{3} \cdot U \cdot I \cdot sin\varphi \tag{8}$$

for three-phase engines acoording formula (8).

The measuring unit is voltamper-reactive (VAR). The reactive power of Q is defined as the power of inductive consumers that is required for the formation of magnetic fields in the network. It is an imaginary energy that is not used in the system, it only burdens and returns energy to the grid.

The oil production system with sucker rod pumps is not linear and during one pumping cycle, loading changes in the system during cycles, so the electrical parameters are also variable over time (Vincetić, 2022).

Given that the system is completed with a frequency converter and a brake resistor, partial compensation of the reactive power can be carried out with thermal energy released on the brake resistor so that this energy does not return to the grid and causes damage to the grid. This compensation amounts to up to 10% of the power of the frequency converter, and in the tested case, it amounts to 1,5kW.

The limitation of such a system is the lack of a recuperator that would direct the reactive power as energy for supplying secondary consumers (lighting, video sensor, etc.). For this reason, by balancing the pumping unit, the aim is to completely eliminate reactive power and use only active power to the system. Then the apparent power taken from the system would be equal to the active power and savings in electricity consumption would be achieved.

Power and power consumption parameters will be shown in tables and graphically on a daily basis. These parameters will be presented by comparison for all five tested wells before and after balancing the system in Table 1.

Table 2. shows the measurement of electricity consumption as well as the savings achieved before and after balancing the pump units on five wells.

Table 2 Consumption and saving of electricity in kWh on a daily basis and in percentage terms

	Before balancing		After balancing		Savings	
Well	Power P(kW)	Electricity consumption (kWh/day)	Power P(kW)	Electricity consumption (kWh/day)	(kWh/day)	%
K-001	2.5	60.7	2.3	55.7	5.0	8%
K-002	2.8	67.2	2.4	57.6	9.6	14%
K-003	1.9	45.6	1.7	40.8	4.8	11%
K-004	3.1	74.4	2.7	64.8	9.6	13%
K-005	3.5	84.0	3.1	74.4	9.6	11%
					Average	11%

The analysis clearly shows that balancing the system leads to a decrease in electricity consumption. For example, a significant decrease in the average power is observed on K-002 well, resulting in daily savings of 9.6 kWh, i.e. 14% in relation to the consumption before balancing. A similar trend has been recorded on other wells, with average savings of 11%.

It could be concluded that, in addition to the savings, the reduction in the working power of the electromotor impacts the reduction in the torque of the gearbox (shown in Figure

10.). In addition to savings, the reduction of the torque of the gearbox extends its service life.

Figure 14. Shows the graphical comparative values of electricity consumption for each of the analyzed wells before and after balancing.

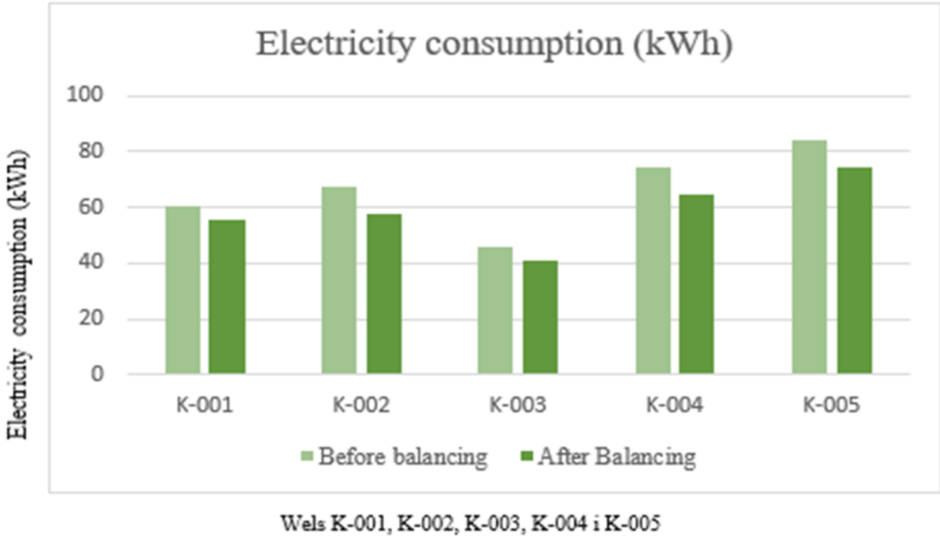
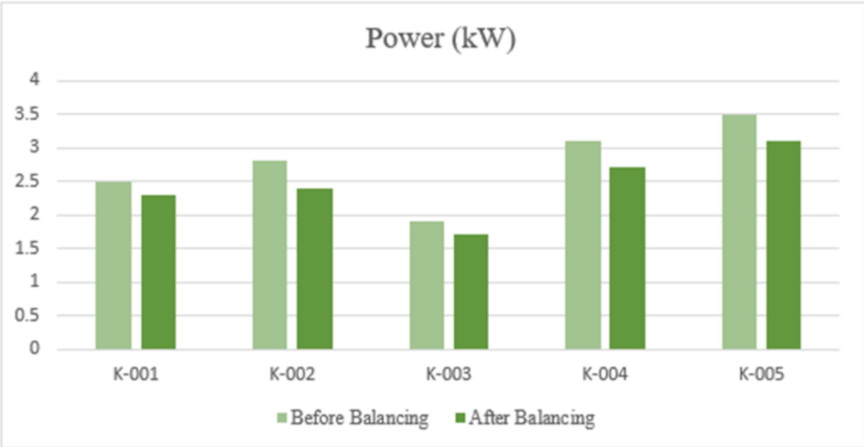


Figure 14 Graphical representation of comparative values of electricity consumption before and after balancing

According to the consumption analysis, it has been concluded that, depending on the nominal motor power, the electricity savings are in the range of 8%-14%, i.e. that the average value of savings in percentage terms is 11%.

Figure 15. shows the comparative values of the power before and after balancing



Wels K-001, K-002, K-003, K-004 i K-005

Figure 15. Graphical representation of comparative values of the power

3.2 Statistical Rigor

In Table 3 and 4 Calculation of average savings and standard deviation is presented.

Table 3 Calculation of average saving

Well	Saving P(kWh)	Saving in (%)
K-001	5,0	8%
K-002	9,6	14%
K-003	4,8	11%
K-004	9,6	13%
K-005	9,6	11%
Average	7,72	11%

Table 4 Standard deviation

Well	Saving P(kW)	Difference from average (kWh)	Square of difference
K-001	5,0	-2,72	7,40
K-002	9,6	1,88	3,53
K-003	4,8	-2,92	8,53
K-004	9,6	1,88	3,53
K-005	9,6	1,88	3,53
		Sum of squares:	26,02

The standard deviation (SD) is calculated according to the equation (9):

$$SD = \sqrt{\frac{\Sigma_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} = \sqrt{\frac{26{,}02}{4}} = 2{,}55\ kWh \qquad (9)$$

The Standard error (SE) represents the ratio of the standard deviation and the root of the number of samples and calculated according to the formula (10):

$$SE = \frac{SD}{\sqrt{n}} = \frac{2{,}55kWh}{\sqrt{5}} = 1.14\ kWh \qquad (10)$$

Confidence intervals for average savings, for the assumed level of call 95% and 4 degrees of freedom (n-1 = 4), value t = 2,776, therefore:

- Upper limit = 7,72kWh + 2,776kWh · 1.14 = 10,89kWh
- Lower limit = 7,72kWh - 2,776kWh · 1.14 = 4,55kWh

The average daily energy savings are 7.72 kWh, with a 95% confidence interval of 4.55 to 10.89 kWh. These values indicate statistically significant energy savings after balance, taking into account the inherent variability in measurements.

Further analysis will consider the impact of operating condition factors such as fluid properties and production variability, which may have a significant impact on system efficiency.

For the wells operating in constant mode with unchanged dynamic level, with a constant number of pump runs and unchanged water content in the produced fluid, the balance is not changed for a long time and the oil production system operates without the need for additional balancing.

In case of a water well increase, the fluid weight in the tubing above the pump system slowly increases, with the increase of the percentage of water in the production fluid falling out of balance. This case occurred in wells in K-001, K-003 and K-005, where after balancing, there is a saving of 8% to 11% in electricity consumption, i.e. an average of 6,47kWh/day per well. A graphic representation of electrical parameters is given in Figure 9. And Figure 10. - (well K-001 - water cut increase from 63% to 92%).

In the event of an increase in production due to a change in operating parameters, the kinematic balance of the system will be disturbed due to a change in the transmission ratio and the pumping speed. Then the system has a big difference in torque and variation of current and power during one cycle. Another impact on imbalance is the deepening of the dynamic level of the well, due to the increase in production by increasing the pumping speed. This type of imbalance has been tested in wells K-002 I K-005. The operating parameters of these wells before and after balancing are given in Table 2, where you can see electricity savings of 13.5% on average, i.e. 9,6kWh/day per well.

Figure 16 graphically presents the electric parameters of the pumping unit before and after balancing. The picture shows that on 12 November 2025, the number of pump walks was changed and the pump unit worked with very high peak currents and forces. After balancing, which was carried out on 15 November 2015. the values of electrical parameters were reduced and electricity consumption was reduced.

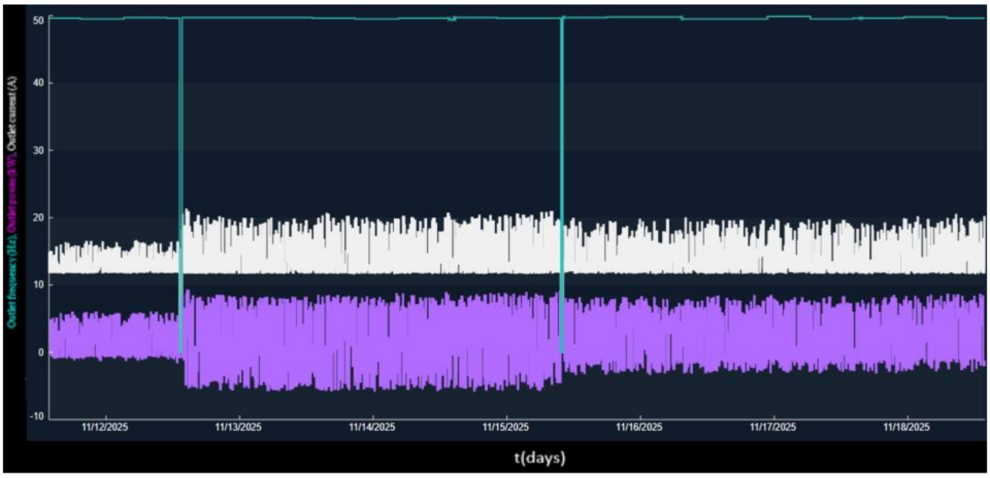


Figure 16. Electrical parameters of the pump operation after increasing the number of walks as before and after balancing the system.

3.3 CO_2 emissions

The calculation of CO_2 emissions is carried out by multiplying electricity consumption (kWh) by the emission factor (kg CO_2/kWh), which represents how many kg of CO_2 is emitted in the production of 1 kWh of electricity.

Equation (CO_2 into kg):

$$\mathrm{CO_2\ kg} = \mathrm{Consumption\ /kWh} \cdot \mathrm{Emission\ factor\ kg/kWh} \tag{11}$$

In tons:

$$\mathrm{CO_2\ in\ t} = \mathrm{CO_2\ kg/1000} \tag{12}$$

Or directly:

$$\mathrm{CO_2\ t} = \mathrm{Consumption\ /kWh} \cdot \mathrm{Emission\ factor\ kg/kWh/1000} \tag{13}$$

The emission factor depends on the network/source (e.g. in Serbia the share of coal is higher, so the factor is significantly higher than in countries with many renewable sources):

- 0.20 kgCO_2/kWh - low value (places with a large share of low-carbon sources)
- 0.50 kgCO_2/kWh - average value (the European average varies around this for mixed networks)
- 0.80 kgCO_2/kWh - high value (places with a lot of coal), Serbia

The empiric factor of 0.80 kgCO_2/kWh was used to calculate CO2 emissions (AERS, 2025; IPCC, 2025).

In table 5 Electricity consumption in (kWh) and CO_2 emissions were presented before and after balancing the tested wells, as well as the reduction of CO_2 emissions in (kg) and percentage on a daily basis.

Table 5 Comparative overview of electricity consumption and reduction of CO2 emissions before and after balancing

	Before balancing		After Balancing		Saving	
Well	Electricity consumption (kWh)	Daily emission of CO_2 (kg)	Electricity consumption (kWh)	Daily emission of CO_2 (kg)	CO2/day (kg)	%
K-001	60.7	48.6	55.7	44.6	4.0	8%
K-002	67.2	53.8	57.6	46.1	7.7	14%
K-003	45.6	36.5	40.8	32.6	3.8	11%
K-004	74.4	59.5	64.8	51.8	7.7	13%
K-005	84	67.2	74.4	59.5	7.7	11%
					Average	11%

Figure 16. shows the comparative CO_2 emissions before and after balancing on all 5 wells tested

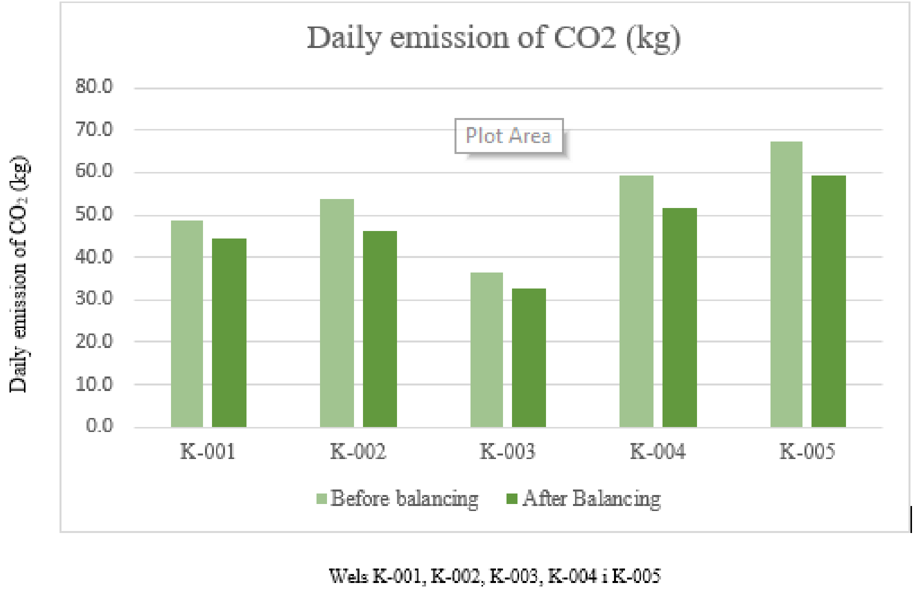


Figure 16. Comparative daily emissions of CO_2 before and after balancing on all 5 wells tested.

3.4 Measurement transparency

Electricity parameters were measured using the SIEMENS SENTRON PAC3220, LCD 96 x 96 mm, Power Monitoring Device, control panel instrument with measurement of electrical variables, protocol: Modbus TCP, with graphical display, Ue rated: 690/400V, 45-65Hz, Ie rated: X/1 A or X/5 A TT, auxiliary power: 100... 250 V + -10% TT/DC. This meter is installed on each of the tested wells in the intelligent control station. This meter is used for continuous measurement of electric current parameters and, in real time, they are sent via MODBUS protocol to the SCADA platform, where parameters are graphically visualised and published through the AVEVA platform. Figure 17 shows the meter used for measuring and monitoring the electrical operating parameters of the downhole equipment.

Figure 17. SIEMENS SENTRON PAC3220

Fulit limits reference condition for metering accuracy in accordance with IEC61557-12, IEC62053-22 and IEC62053-23.

Relative total measurement inaccuracy:

1. For measured variable voltage +/- 0.2 %
2. For measured variable current +/- 0.2 %
3. For measured variable active power +/- 0.5 %
4. For measured variable reactive power +/- 1 %
5. For measured variable output factor +/- 0,5 %
6. For measured variable active energy Cl. 0.5 acc. to... IEC62053-22

For measured variable reactive energy Class 2 according to IEC61557-12 and/or IEC62053-23

3.5 Limitations and future works

Limitations in obtaining precise electrical parameters presupposes the problem of data storage on the server. In order to avoid overloading the server, sending data from the well via the MODBUS protocol is done once in 30 seconds. In this way, we cannot get a complete curve that represents the movement of engine power and current strength parameters in one pump operating cycle. This approach makes it impossible to remotely spot engine power and current peaks. On the graphics displayed as visualization in the AVEVA platform, only minimal and maximum values of these sizes can be observed. To some extent, this data can refer to problems in operation (system imbalance) if the engine power and current strength values increase over time from the nominal for a given electric motor to the maximum value.

In that case, the measurement of current strength at the engine phases at the location is initiated. By measuring the current strength in one pump cycle, peaks are recorded in the diagram, through the analysis of which we obtain information about the degree of system imbalance. In Figure 18. The corners of the four pumping unit weight positions (0^{O}, 90^{O},180^{O}, and 270^{O}) are shown.

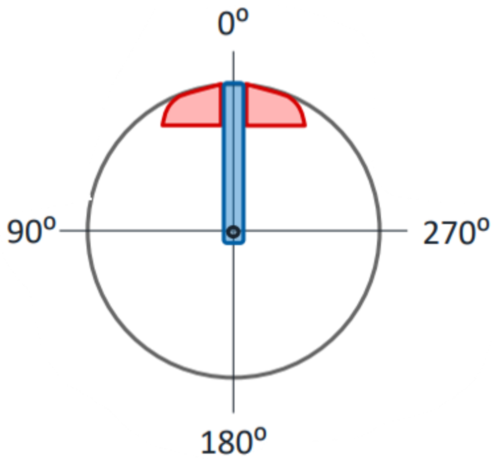


Figure 18. Weight position angles for one pump operation cycle

Based on the measured strength of currents when the weights are in the 90^{O} and 270^{O} position, we can calculate the system imbalance coefficient through the equation (14):

$$k = \frac{\mathrm{I}\,90° - \mathrm{I}\,270°}{\mathrm{I}\,90° + \mathrm{I}\,270°} \cdot 100 \qquad (14)$$

If the value of the coefficient k> 5, we believe that the system is in balance and needs balancing.

This type of measurement is performed using the Fluke 355/353 True-rms 2000 A Clamp Meters device.

Measurement accuracy for currents higher than 10A is shown in Table 6.

Table 6 Measurement accuracy of Fluke 355/353 True-rms 2000 A Clamp Meters

Range	Resolution	Accuracy
40 A	10 mA	3.5 % rdg + 15 digits 0.50 A 2.50 A 0.50 A
400 A	100 mA	3.5 % rdg + 5 digits 5.0 A 2.5 A 2.5 A
2000 A	1 A	3.5 % rdg + 5 digits 5 A 8 A 8 A

This method of determining the imbalance of the System is reliable, but requires additional engagement of operators in the field.

For future operation, the use of the Node-RED platform for online recording of motor power diagrams and real-time current strength for one pumping cycle are under preparation. After implementing this approach and using artificial intelligence, the identification of the System's imbalance will be fully automated and will alarm this work disruption in real time.

For now, it remains an open question and space for exploring the method of used AI for these cases. The layout of the diagrams recorded using Node-RED, which is currently in testing, is shown in Figure 19. The X-axis represents the recording time and the Y-axis represents the engine power P (kW).

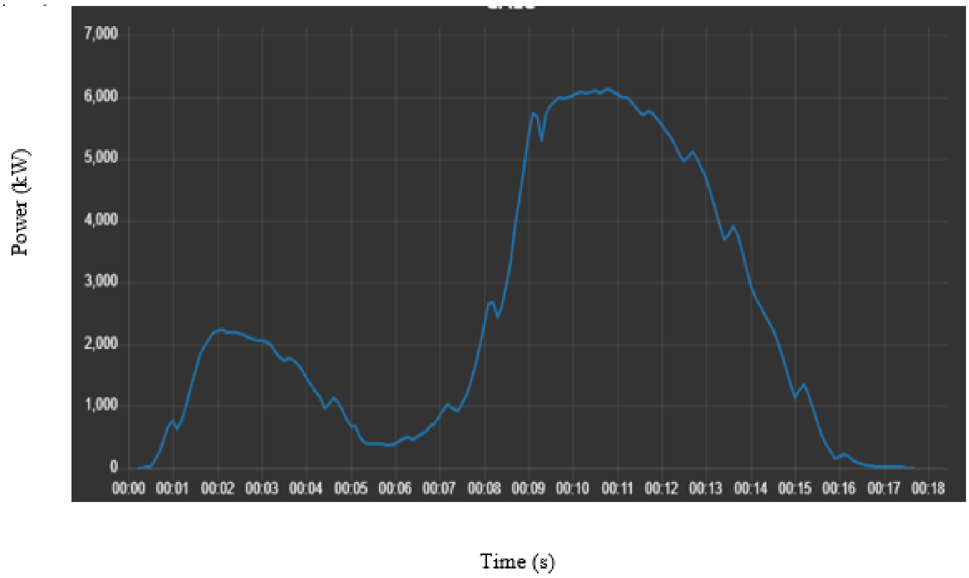


Figure 19. Diagram taken during one pump operation cycle

3.6 Economic profitability

The system for remote monitoring of the oil production system with piston pumps is complex and is used for monitoring a large number of parameters and collecting a large number of data that are used for analysis and making decisions for taking over the activities in order to optimize the product, with reduced costs and increased reliability of work.

The analysis of electricity savings is only one in a series of analyses that needs to be carried out and in order to determine the profitability of the installation of the remote monitoring system. These analyses remain an open topic for subsequent works, and the sum of all analyses will give a unique conclusion that will prove hypotheses about profitability in the shortest possible time and with countless benefits reflected not only in the financial perspective but also in the profit in the field of environmental protection and occupational health and safety in the oil industry.

Certainly, part of the impact on economic profitability has been proven through this work.

4 CONCLUSION

This research paper analyzes the key components of optimizing oil production through sucker rod pumps, with an emphasis on maintaining optimal system balance. Through the application of modern technologies, especially the intelligent monitoring and predictive maintenance system, significant results have been achieved in reducing operating costs, increasing efficiency and extending the service life of the equipment.

It has been identified that traditional maintenance methods, which rely on a schedule of regular interventions, are not effective enough in preventing downtime and failures. Given the complexity of modern systems, a condition-based maintenance (CBM) approach has proven to be a superior strategy. This approach allows maintenance decisions to be made based on the actual condition of the equipment, which leads to a reduction in the frequency of interventions and optimization of resources.

The analysis of the collected data from five oil wells has revealed that the application of predictive maintenance and the system balance results in a reduction in electricity consumption in the range of 8% and 14%, with average savings of 11%. These savings not only reduce the operating costs, but also contribute to reducing the negative impact on the environment, thus meeting modern environmental standards.

Remote monitoring of the system performances in real time enables a faster response to irregularities and potential problems, which further reduces the risk of production downtime. By introducing an intelligent management system, the monitoring specialists are able to identify and solve problems in a timely manner before significant consequences occur, which further optimizes the production process.

The research has also found that proper system balancing not only improves the operational efficiency of the pumps, but also reduces the stress on the mechanical components, thus extending their service life. This aspect is of particular importance for reducing the costs of maintenance and replacement of the equipment, especially in the context of the increasing demands for sustainable development of the industry.

In conclusion, optimization of oil production by sucker rod pumps through maintaining optimal system balance is a key component for increasing efficiency and reducing costs in the industry. This paper provides a basis for further research and application of modern technologies in the oil industry, with the aim of achieving a more sustainable and profitable business. The combination of modern monitoring and analysis methods, together with predictive maintenance, enables proactive production management and contributes to the global goals of energy efficiency and environmental protection.

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Original scientific paper

INVESTIGATION OF PRE-CONCENTRATION OF THE LECE ORE USING DENSE MEDIUM GRAVITY CONCENTRATION

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Abstract: The pre-concentration of Pb–Zn ores is commonly performed using gravity concentration in a dense medium. The primary objective of this process is to remove coarse-grained gangue from fully crushed ore using a cost-effective method, while keeping the loss of valuable metals within acceptable limits—comparable to or lower than those observed in flotation processes.

Laboratory tests on ore from the Lece deposit indicate that gravity concentration in a dense medium can successfully remove over 60% of coarse-grained gangue from fully crushed ore. From a process applicability standpoint, this represents a promising result. However, the associated losses of valuable metals—particularly gold and silver—are substantial, reaching approximately 50%. Gold is the most valuable component in the Lece ore. Therefore, pre-concentration at the final crushing stage is not considered feasible at industrial scale.

Keywords: Pb–Zn ores, pre-concentration, gravity concentration, dense medium, pre-concentrate, coarse-grained gangue, metal recovery

1 INTRODUCTION

Gravity concentration in a dense medium can be applied as a pre-concentration method for ores, particularly when coarse-grained gangue—representing at least 40% of the total mass—is removed, while ensuring that metal losses in the gangue remain lower than in the primary beneficiation process (Ćalić, 1990).

The applicability of gravity concentration is typically assessed through sink–float (S–F) analysis, in which coarse-grained gangue is separated at different densities under

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laboratory or pilot-scale conditions. The separated products are chemically analyzed, and a pre-concentration mass balance is prepared (Deušić and Lazić, 2013).

This study presents the results of laboratory-scale testing on fully crushed ore from the Lece deposit, focusing on the potential application of dense-medium pre-concentration. The final decision on implementing pre-concentration in a dense-medium suspension is always based on a comprehensive economic analysis (Dardis, 1985).

Pre-concentration generally yields a more favorable particle size distribution of the pre-concentrate compared to run-of-mine (ROM) ore. This is primarily because hard, coarse-grained gangue is removed prior to grinding, which positively affects energy efficiency during milling (Motovilov et al., 2019). In addition, the removal of hard, coarse-grained gangue frees up flotation plant capacity proportional to the mass of material rejected through pre-concentration, allowing increased mine throughput without significant investment in flotation facilities (Kolacz, 2017).

Besides dense-medium-based pre-concentration, other methods such as X-ray and optical sorting have also been reported (Karami et al., 2019). Nevertheless, gravity concentration remains one of the oldest mineral processing methods, having been used for more than a century (Legault-Seguin et al., 2016).

Gravity concentration in a dense medium is a robust process capable of handling particles of varying sizes (from 300 mm down to 0.5 mm), provided prior liberation of mineral grains has been achieved (Sheng et al., 2019). Continuous advancements in equipment and process design, including the development of a biconical cyclone for separation in suspensions, have demonstrated promising results (Motovilov et al., 2019).

2 MATERIALS AND METHODS

The Lece ore primarily consists of sulfide minerals and quartz, with a relatively limited variety of mineral species. Ore minerals in the open-pit zone of the deposit formed at low temperatures. The main minerals present include sphalerite, galena, pyrite, chalcopyrite, and gold-bearing quartz (Lece Mine, n.d.).

Sphalerite is one of the most widespread and abundant sulfide minerals in the deposit. It rarely occurs in coarse crystals, being mostly fine-grained, and contains cadmium. Sphalerite in the deposit formed in three distinct stages (Lece Mine, n.d.).

Galena, together with sphalerite, represents the most important mineral in the deposit. The majority of galena occurs as fine-grained crystals and mineral aggregates. Galena formed in three stages; the largest portion belongs to the third stage, a smaller amount to the second, and the least to the first. Galena from the second and third stages occurs without segregation, forming crystalline masses and nests; it contains gold and silver, and is thus referred to as gold-bearing galena. Galena replaces older minerals and is most commonly replaced by pyrite. It is fractured and cataclastic. In the oxidation zone, galena is coated with a thin to thick crust of cerussite (Motovilov et al., 2019).

Pyrite is widespread in the deposit, occurring as rounded granular aggregates, indicative of formation from a gel. Chalcopyrite often cements pyrite and partially replaces it. Pyrite grain size varies but is mostly in the range of 4–5 mm. Pyrite contains traces of gold and silver (Motovilov et al., 2019). Due to the presence of gold and silver in pyrite, a pyrite flotation process has been developed, and the flotation plant at the Lece mine currently produces three concentrates: lead concentrate, zinc concentrate, and pyrite concentrate.

Chalcopyrite is the primary copper-bearing mineral and is always present in small amounts in the ore. Gold occurs in the ore as native metal, found within quartz, galena, sphalerite, and pyrite, typically in rounded forms (Kolacz, 2017).

The tested material, weighing 13.73 kg, was obtained from the Lece mine. This sample represents fully crushed ore taken from the conveyor belt feeding the ball mill. After determining the sample mass, it was sieved through a series of five sieves with mesh openings of 40 mm, 30 mm, 15 mm, 10 mm, and 5 mm to determine the particle size distribution of the feed sample.

The objective of this research was to investigate the potential for pre-concentration by immersing the ore sample in a bromoform ($CHBr_3$) solution. Since it is recommended that fine size fractions –3(2.5) +0 mm are not subjected to pre-concentration, wet sieving (washing) of the entire sample was conducted on a 2.5 mm sieve. The –2.5 +0 mm size fraction was not immersed in bromoform but was dried, weighed, and chemically analyzed separately.

The mass of the +2.5 mm size fraction was 10.15 kg, while the –2.5 +0 mm fraction weighed 3.58 kg. Prior to conducting the sink–float analysis on the +2.5 mm size fraction in the dense medium, the density of the dense liquid (bromoform, $CHBr_3$) was measured using a pycnometer, yielding a density of 2.67 g/cm^3. This relatively low density, close to that of quartz gangue, was chosen deliberately to minimize metal losses in the coarse gangue, even though it may lead to a low yield of the ΔL fraction (coarse gangue). Therefore, these results are considered preliminary.

After stratification of the entire +2.5 mm material, the vessels containing the heavy (ΔT) and light (ΔL) fractions were dried in a ventilated oven. Once dried, the masses of the light and heavy fractions were measured. The heavy fraction (ΔT) weighed 1,650 g, and the light fraction (ΔL) weighed 8,500 g.

Subsequently, the samples were processed and prepared for chemical analysis. This preparation included multi-stage comminution (crushing and grinding), homogenization, and sampling of material for chemical analysis (approximately 100 g per sample, with particle size below 100 μm) (Sheng et al., 2019).

3 RESULTS AND DISCUSSION

The experimental results are presented below, together with a detailed analysis and discussion.

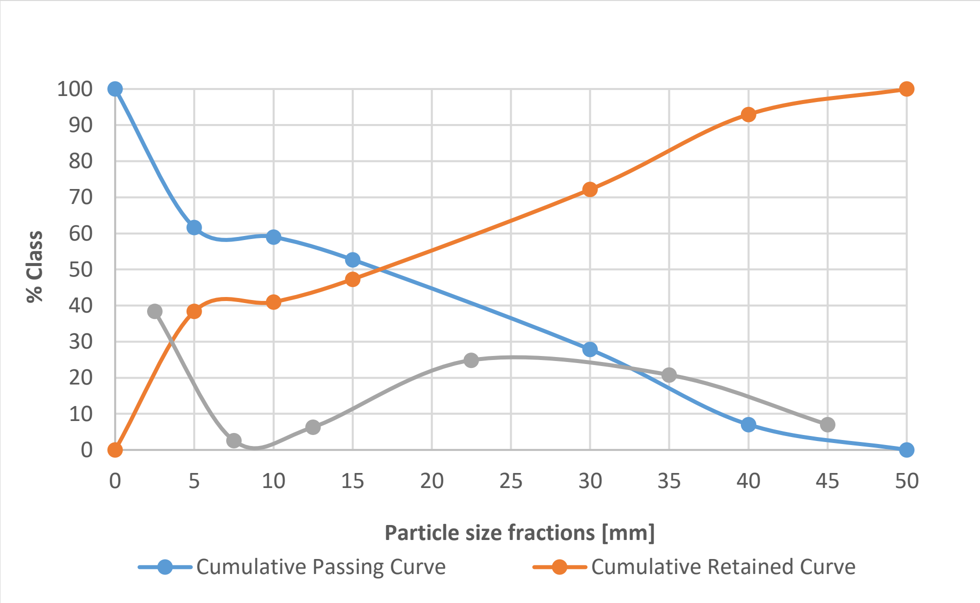

Figure 1 Graphical representation of the particle size distribution of the feed sample

From the particle size distribution diagram (Figure 1), the median particle size (d_{50}) was determined to be 16 mm by intersecting the cumulative oversize and undersize curves with the 50% mass line. The upper limit of the coarse particle size (d_{95}) was read as 44 mm by extending a line from 95% mass on the ordinate to intersect the undersize curve.

The frequency distribution curve represents the mass proportion of each size class, illustrating the relative distribution of particle sizes. In this sample, the most abundant size class by mass is the -5 +0 mm fraction, accounting for 38.38%, whereas the least represented class is the -10 +5 mm fraction, accounting for 2.60%.

Following dry sieving and determination of the particle size distribution, the sample was wet sieved on a 2.5 mm sieve. The undersize fraction (-2.5 +0 mm) was dried, weighed, and submitted for chemical analysis. Sink–float analysis was conducted on the oversize fraction (+2.5 mm), producing two fractions: the heavy fraction (ΔT) and the light fraction/gangue (ΔL). The heavy fraction was then combined with the untreated undersize material (-2.5 +0 mm) to form the pre-concentrate.

The mass balances of the sink–float analysis and the pre-concentration process are presented in Tables 1 and 2.

Table 1 Sink–float analysis balance

Products	M, [kg]	M, [%]	Pb, [%]	Zn, [%]	Au, [g/t]	Ag, [g/t]	I Pb, [%]	I Zn, [%]	`I Au, [%]	I Ag, [%]
Feed	13.73	100.00	0.43	1.03	3.58	6.16	100.00	100.00	100.00	100.00
ΔT	1.65	12.02	0.86	3.35	2.30	8.03	23.86	39.00	7.71	15.68
ΔL(Taili-ngs)	8.5	61.91	0.12	0.28	2.90	3.57	17.15	16.79	50.09	35.91
-2,5 mm	3.58	26.07	0.98	1.75	5.80	11.43	58.99	44.21	42.20	48.42

Based on the mass balance results of the sink–float analysis, it can be concluded that the process was effective in removing coarse-grained gangue, with 61.91% of the feed material separated into the light fraction (gangue). In general, pre-concentration is considered viable when this value exceeds 40%. By combining the heavy fraction with the -2.5 mm size fraction, which was not subjected to gravity concentration, the pre-concentrate was obtained.

The chemical analysis of the pre-concentrate and gangue fractions revealed that the pre-concentrate contained the majority of the valuable metals, while metal losses in the light fraction were minimized. However, significant losses of gold and silver were observed, reflecting the need to carefully consider the economic feasibility of applying dense-medium pre-concentration at the final crushing stage.

The particle size distribution of the pre-concentrate also showed a higher proportion of finer particles compared to the original feed, which is advantageous for subsequent grinding and flotation processes, as it reduces energy consumption and improves the efficiency of downstream operations.

Table 2 Mass and metal balance of preconcentration

Products	M, [kg]	M, [%]	Pb, [%]	Zn, [%]	Au, [g/t]	Ag, [g/t]	I Pb, [%]	I Zn, [%]	I Au, [%]	I Ag, [%]
Feed	13.73	100.00	0.43	1.03	3.58	6.16	100.00	100.00	100.00	100.00
-2,5 [mm] + ΔT	5.23	38.09	0.94	2.25	4.70	10.36	82.85	83.21	49.91	64.09
Tailings	8.50	61.91	0.12	0.28	2.90	3.57	17.15	16.79	50.09	35.91

According to the results of this mass balance, the effectiveness of the pre-concentration test can be assessed from two perspectives. The process successfully removed a substantial portion of coarse-grained gangue (61.91%), which contained 0.12% Pb and 0.28% Zn. The losses of lead and zinc in the tailings were approximately 17%, which is slightly higher compared to the losses observed in flotation tailings. This could potentially be mitigated by applying a lower suspension density during the pre-concentration process.

However, the loss of gold in the coarse-grained tailings—approximately 50%—is considered unacceptable, as is the silver loss of about 36%. These results suggest that a significant portion of gold and silver is associated with quartz, since, at the density used for stratification (2.67 g/cm^3), quartz reported to the tailings. From an economic perspective, this outcome could be beneficial because quartz, with a Mohs hardness of 7, is difficult to grind, thereby reducing energy requirements during milling. Nevertheless, the ore exhibits a heterogeneous and complex composition, and gold occurs within quartz minerals in the form of fine filaments. Consequently, the transfer of quartz into the light fraction resulted in substantial losses of gold and silver in the tailings.

4 CONCLUSION

The pre-concentration of ore, when applicable, can offer significant savings in the overall ore processing operation.

Based on the analysis of the obtained pre-concentration mass balances of the crushed ore from the Lece deposit, it can be concluded that the process is applicable in terms of the mass fraction of coarse-grained gangue. Specifically, when more than 40% of the material reports to the light fraction, the pre-concentration process is considered feasible. In this study, the ΔL value reached 61.91%, indicating economic viability from this perspective.

At the stratification density of 2.67 g/cm^3, a large portion of quartz reported to the light fraction (tailings), which could provide considerable advantages in subsequent grinding stages. Quartz, with a Mohs hardness of 7, is difficult to grind, so its removal reduces energy consumption, wear on mill liners, and abrasion of grinding media. Furthermore, by removing over 60% of the gangue through pre-concentration, the amount of material requiring grinding—and subsequently flotation—is substantially decreased, allowing for potential increases in plant throughput.

The pre-concentration process would also reduce the volume of fine-grained flotation tailings discharged to the tailings pond, positively affecting environmental management.

However, the main limitation of applying this pre-concentration method is the significant loss of gold and silver to the tailings. As noted, quartz reported to the light fraction, and because the ore has a heterogeneous composition, part of the gold occurs within quartz as fine filaments. Consequently, the gold loss in the tailings is approximately 50%, while silver loss is around 36%.

Considering all these factors, it can be concluded that the pre-concentration process, as applied to the crushed ore from the Lece deposit, is not suitable for practical industrial implementation.

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Original scientific paper

SELECTING THE SUITABLE ROCK EXCAVATION METHOD OF HARD ROCK REMOVAL FOR CONSTRUCTING A GROUND LEVEL SERVICE RESERVOIR AT HILL TOP IN URBAN POPULATION

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Abstract: A best-suited method for rock excavation at the hilltop has been identified in the present paper for construction of a Ground Level Service Reservoir (GLSR) in a densely populated urban area. At the foothill, several residential houses are located at 70 meters from the excavation boundary. Due to presence of hard granitic rock, the previously adopted method using a non-explosive silent cracking agent combined with hydraulic rock breakers and excavators became inefficient in achieving the required production targets. Hence, various alternative rock excavation methods were evaluated considering two key factors, timely completion and safety of nearby structures.

Various rock-breaking techniques such as hydraulic rock breakers, static expansion agents, plasma blasting and heat-assisted splitting were reviewed thoroughly, but they found to be time-consuming and inadequate for completing the project within the time schedule. The use of explosives and controlled blasting method emerged as the only viable option provided the emanating ground vibrations, noise, and flyrock are maintained within permissible limits. Based on data from different sites with similar geological conditions, a vibration prediction equation was developed and accordingly, appropriate controlled blasting patterns along with an optimized excavation methodology were proposed to ensure safe rock excavation within the designated timeframe.

Keywords: Rock excavation, Controlled blasting, Ground vibrations, Ground Level Service Reservoir (GLSR), Non-explosive rock breakage methods

1 INTRODUCTION

In order to ensure uninterrupted availability of drinking water in Ranchi city, the capital of Jharkhand, the State Government has initiated the Jharkhand Urban Water Supply

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Improvement Project (JUWSIP). Ranchi, governed by the Municipal Corporation comprising of 55 wards within approximately 174 km² area.

The water demand of Ranchi is projected to rise sharply, reaching 401.36 MLD by 2035 and 556.81 MLD by 2050. Although a 114 MLD water treatment plant has been commissioned in 2018 under the AMRUT scheme of the Ministry of Housing and Urban Affairs to improve the water supply in Ranchi's northwestern and southern sectors, many challenges still persist. These include low per capita availability, irregular supply hours, insufficient pressure in peripheral areas and uneven distribution of water across zones (Government of Jharkhand Report, 2021).

The service-level indicators of 2022 (Table 1) indicate that the household water connection coverage and per capita supply are still below the prescribed urban service benchmarks (Urban Development & Housing Department Notification, 2022). To address this, the State Government proposed to develop an upgraded water supply system consisting a 213 MLD Water Treatment Plant (WTP), a 28.8 ML Ground Level Service Reservoir (GLSR) and a 489,268 m long distribution network for 60,932 household connections (Government of Jharkhand Report, 2021). This system is expected to enhance the existing infrastructure and meet the city's growing demand.

Table 1 Water Supply Service Levels for Ranchi City, Jharkhand

Sl. No.	Indicator	Benchmark	Status for 2021-22	Target for 2022-23
1	Coverage of water supply connections	100 %	60	65
2	Per capita supply of water	135 LPCD*	73	80
3	Extent of metering of water connections	100 %	28	40
4	Extent of non-revenue of water	20 %	38	35
5	Continuity of water supply	24 Hours	3	3
6	Efficiency in redressal of customer complaints	80 %	99	100
7	Quality of water supplied	100 %	100	100
8	Cost recovery in water supply services	100 %	7.8	45
9	Efficiency in collection of water supply related charges	90 %	30	45

*LPCD is for Liters per capita per day

Under this new water supply system, a Ground Level Service Reservoir (GLSR) is to be constructed at the top of a Hill, Bharamtoli Hill in the northern side of the Ranchi city (Figure 1). The construction of GSLR at a slightly higher elevation level would be benefitted due to following reasons:

a. Gravity-assisted distribution: The gravity-driven distribution from a higher elevation level would minimize the dependence on energy-intensive pumping and therefore, improve the efficiency.

b. Improved water pressure: The natural height would provide better pressure throughout the network thereby ensuring consistent service even during peak demand conditions also.

c. Emergency supply: During power outages or pump failures, gravity flow will maintain the water supply for critical services such as firefighting and sanitation.

d. Reduced contamination risk: Elevated reservoirs would be less vulnerable to ground-level contamination ensuring safer and cleaner water.

Figure 1. View of the GLSR construction site on top of Bharamtoli Hill (Source: Google Earth)

The hill is surrounded by many residential houses and hutments at the foothill on the north, west, and east sides. The reservoir would be divided into two compartments, covering an area of 100 m x 100 m with a tank size of 70 m x 70 m. The highest elevation level (EL) of the hill is 700 m, and excavation of hard rock is planned down to 687 m EL to construct the reservoir. The proposed maximum and minimum water levels within the GLSR are 693.00 m and 687.00 m, respectively, while the foothill's elevation is 629 m. The layout plan, illustrating the GLSR and nearby structures, is shown in Figure 2.

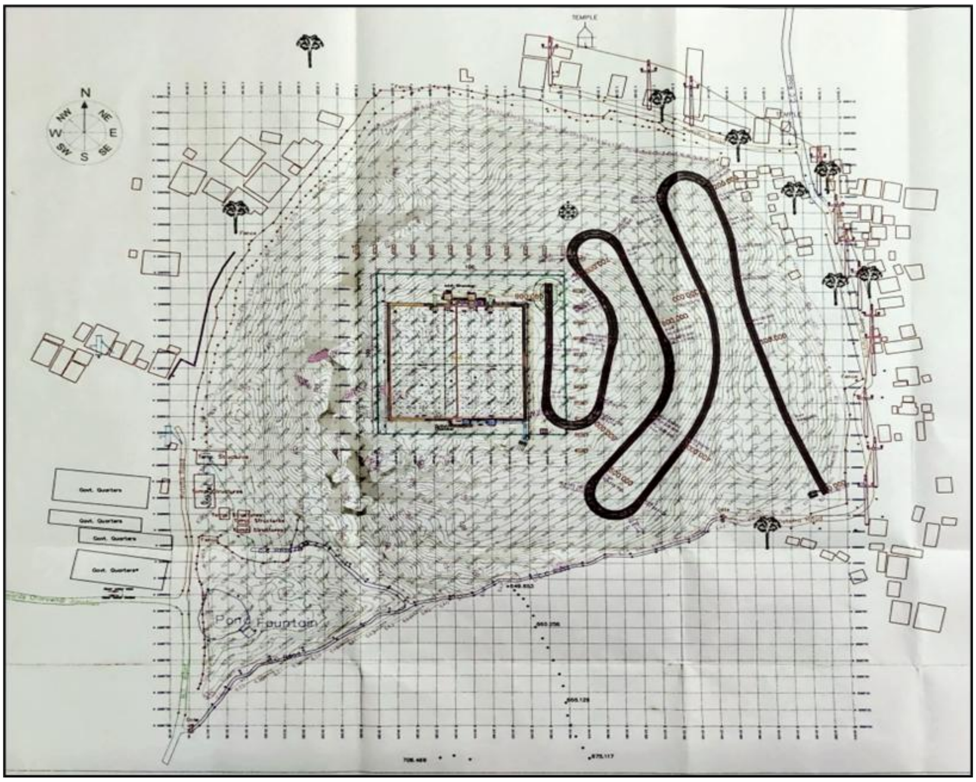

Figure 2. Plan view of the proposed GLSR showing different structures at the foothill

Due to its location in a densely populated area, the hard rock excavation at the hilltop is being carried out by using chemical expansive powder poured into shot holes drilled by jackhammer drilling machines. Once cracks develop after a considerable time duration, the subsequent excavation work is done by hydraulic excavators and rock breakers. However, this method produces very low daily output, posing risks to meet the construction schedule. To expedite the progress, alternate rock excavation techniques were investigated, and a detailed study was taken to identify the most effective, safe and timely rock excavation method for constructing the GLSR in time without endangering nearby residential structures. The paper provides a comprehensive analytical review of various rock breakage techniques and their evaluation to identify the safest and most effective method for hard rock excavation at the GLSR construction site on Bharamtoli hill.

2 SITE DETAILS AND GEOLOGY OF THE AREA

The GLSR construction site is situated on top of the Bharamtoli Hill in the northern part of Ranchi. Ranchi lies in the southern section of the Chhotanagpur Plateau (CNP), which forms the eastern extension of the Deccan Plateau. The city's primary water supply comes from major reservoirs created by damming the Kanke, Rukka, and Hatia channels.

The landscape of Jharkhand is predominantly influenced by the Chhotanagpur Plateau and its associated geomorphic divisions. Extending from the state's western region to its eastern boundary with West Bengal, the CNP exhibits a wide range of landform features. The Ranchi Plateau, the largest part of this formation, has an average elevation of approximately 700 meters above mean sea level (DOM&G, Government of Jharkhand, 2010). Geologically, the Ranchi Plateau rests primarily on hard crystalline rocks such as gneisses and granites, which are remnants of the ancient consolidated crust formed during the Archaean era more than 1,200 million years ago. The bedrock also includes schists and quartzites, together constituting the dominant lithological units of the region's hills and plateau areas (Pathak, 2012). From the peak of Bharamtoli Hill (Figure 3), rock samples were collected and analyzed at the Rock Mechanics Laboratory, CSIR-CIMFR, Dhanbad, to determine its various physico-mechanical properties. The hill consists mainly of granite, a very hard rock, and the results of these tests are summarized in Table 2.

Figure 3. A view of the type of rock observed on top of the Bharamtoli Hill

Table 2 Different physico-mechanical properties of the rock strata of the Bharamtoli Hill

Rock Type	Density (Dry)		Uniaxial Compressive Strength		Tensile Strength		Young's Modulus		Poisson's Ratio	
	Kg/m^3	Avg.	MPa	Avg.	MPa	Avg.	GPa	Avg.		Avg.
	2646		90.07		9.47		12.24		-	
Granite	2640	2643	59.04	76.37	7.37	8.83	9.15	11.51	0.34	0.29
	2644		79.99		9.66		13.13		0.23	

3 EXISTING PRACTICE OF ROCK BREAKAGE

The top of Bharamtoli Hill is composed of hard granite rock. The hill's top Elevation Level (EL) is 700 m, while excavation for construction of the GLSR is required down to EL 687 m, resulting in an average excavation depth of about 9 m. Currently, rock removal is performed using non-explosive methods. The process involves the use of a powdery expansive agent known as Echocrack, which initiates controlled fractures in the granite. L&T Komatsu PC 200 hydraulic rock breakers are then employed to break the rock mass along the cracks formed by the non-explosive agent.

To create these cracks, holes of 32 mm diameter are drilled using Jack Hammer Hydraulic drilling machines (Figure 4). The holes typically range from 1.2 to 1.5 m in depth, with a spacing of 0.20 to 0.30 m between them (Figure 5). The non-explosive chemical powder is then mixed with water in an appropriate ratio and poured into the drilled holes, leaving the top 0.3–0.4 m unfilled. This remaining portion is then packed tightly with the drill cuttings (Figure 6).

The diluted chemical gradually expands within the holes and generates an internal pressure which in turn, fractures the rock and produces cracks along the drilled hole lines. The cracking process generally takes 12-24 hours but, does not produce any noticeable displacement of the rock mass. Once the cracks are developed, hydraulic rock breakers are used to further reduce the rock to the required size (Figure 7).

Six numbers of Jack Hammer Drilling Machines of 32 mm hole diameter are used to drill the holes and are employed for about 8 hours per day. Following the complete process of drilling, charging, and crack formation, approximately 50–70 m^3 of rock is broken daily. As of the site visit date, around 8,000 m^3 of rock has been excavated from Bharamtoli Hill within a 7 months duration.

The GLSR project, including related distribution works, is scheduled for completion within 36 months. The total volume of rock to be excavated is estimated at 44,000 m^3 across an area of 100 m x 100 m. After seven months of excavation, an estimated 36,000 m^3 of rock remains. At the current removal rate of roughly 60 m^3 per day, an additional 600 days will be needed to complete the excavation (36,000 ÷ 60 = 600).

Thus, to completely excavate the balance volume of rock, 600 days are still required with this method. Therefore, a comprehensive technical review of the alternate rock-breaking methods with an increased focus on explosive and blasting method is in underway to determine the most efficient and safe method of rock breakage to ensure timely completion while maintaining the structural integrity of nearby residential areas at the base of the hill.

Figure 4. Use of 32 mm diameter Jack Hammer Drilling Machine for drilling of holes

Figure 5. Drilling pattern of holes (20-30 cm spacing)

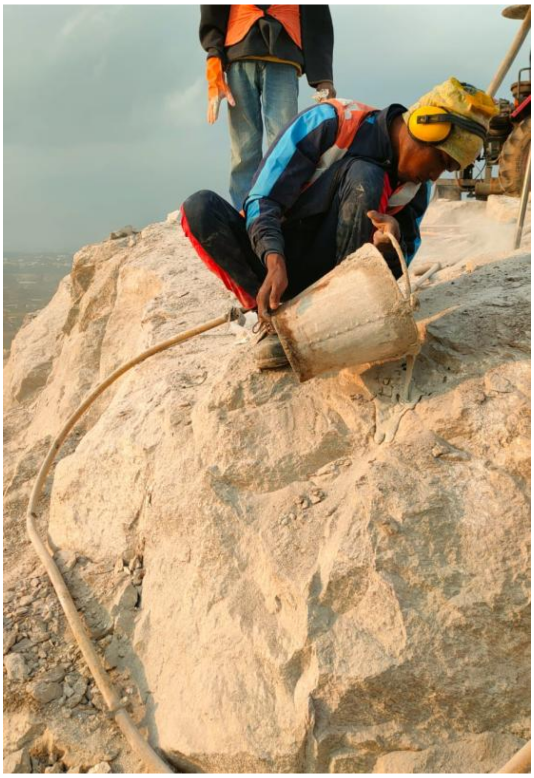

Figure 6. Pouring of non-explosive chemical in the hole

Figure 7. Use of Hydraulic Rock Breakers to break the cracks generated by the non-explosive agent

4 ASSESSMENT OF SAFE METHOD OF ROCK BREAKAGE

4.1 Different methods of rock breakage

Several methods are used for rock breakage in mining and civil engineering projects, depending on site-specific factors such as rock type, geological conditions, production requirements, equipment availability, proximity to structures, and potential environmental impacts. The most common methods include the following:

4.1.1 Explosive and blasting method

The use of explosives and blasting is the primary technique for rock breakage in most mining and civil engineering operations due to its high productivity at relatively lower cost compared to other methods. Despite advancements in mining technologies, blasting continues to be the most widely adopted rock breakage method throughout the world.

In this method, holes of required depth are drilled into the rock surface according to production requirements. These holes are then charged with commercially available explosives up to a certain depth and the balance hole is stemmed properly. After making proper connections with delay detonators, the shot is safely detonated from a secure location. The resulting fragmented rock is subsequently excavated using heavy earth-moving machineries. Although this method is economical and efficient, it may cause undesired effects such as ground vibration, noise, air overpressure, flyrock, dust, and fumes (Al-Bakri & Hafni, 2021).

4.1.2 Non-explosive methods

Non-explosive methods are widely employed in rock breakage at sensitive sites such as populated areas, high-risk zones, road excavation projects, and locations with complex environmental conditions. These techniques can be broadly classified into mechanical, chemical, and electrical methods (Zhou & Feng, 2018). Mechanical methods use large equipment such as hydraulic splitters, hydraulic breakers, and boring machines to fracture or cut the hard rock. Chemical methods involve the use of agents like static expansion compounds, carbon dioxide crackers, and metal burners. Electrical methods employ technologies such as plasma blasting and thermal splitting to break rock. A summary of various non-explosive rock breakage methods is presented in Table 3.

Table 3 Comparison of different non-explosive rock breakage methods

Type		Economy	Application / scope	Advantage	Disadvantage
Mechanical	Hydraulic Splitting Machine	Normal	Mines, gemstones, etc.	Safe to use, generates minimal vibration, environmentally friendly	Mechanical parts wear quickly, relatively low efficiency
	Hydraulic Breaker	Normal	Municipal works, mountainous terrain, ice breaking, demolition	Safe and eco-friendly	Prone to wear, unsuitable for medium-hard rock
	Boring Machine	Higher	Coal mines, tunneling projects	Safe, environmentally sound, delivers good quality results	Subject to wear, structurally complex, maintenance-intensive
Chemical	Static Expansion Agent	Low	Quarries, concrete structures	No flying debris, vibration-free, environmentally safe	Performance affected by rock type and climate, low efficiency
	Carbon Dioxide Cracker	Low	Quarries, coal mines, concrete	Very safe, produces minimal vibration	Standards lacking, some safety risks remain
	Metal Burners	Higher	Gemstone mining	No flying fragments, no toxic gases	Generates waste metal, reactive metals can be hazardous
Electrical	Plasma Blasting	Normal	Dismantling, Municipal Engineering	High safety, low vibration, no flying debris	Equipment costly, produces limited rock fragmentation
	Heat Splitting Rock	Normal	Supplemental rock breakage	Very effective on hard rock	Only suitable as a secondary method

4.2 Evaluation of safe rock breakage method

After a comprehensive review of various rock breakage techniques and their respective advantages and limitations, it has been determined that, under the present conditions at the GLSR construction site, all non-explosive methods, such as mechanical type hydraulic rock breakers, chemical-based static expansion agents, electrical plasma blasting, and heat-induced rock splitting are inefficient for the required scale. These methods are considerably slow, time-consuming, and unable to deliver the necessary daily output of fractured rock essential for completing hard rock excavation within the scheduled timeframe. Furthermore, several of these non-explosive techniques are either impractical or currently unavailable in Indian conditions. Hence, the adoption of explosive-based blasting methods has become indispensable to achieve the project's objectives within the desired timeline. Nevertheless, a safety assessment of this method is imperative, particularly for ensuring the protection of structures situated at the foothill area.

Blasting with explosives provides a rapid and effective means for breaking large rock masses. However, it carries potential risks and disturbances if not designed and executed with careful consideration of all relevant parameters. Properly controlled blasting operations can significantly accelerate the excavation process while maintaining their impacts such as ground vibrations, air overpressure, noise, and fly rock within permissible limits defined by Indian regulatory authorities. Therefore, a detailed evaluation of the blasting impacts, with a particular focus on ground vibrations affecting nearby foothill structures, is essential before finalizing the design parameters for the GLSR construction site.

4.2.1 Assessment of impact of ground vibrations in explosive and blasting method

Several studies on controlled blasting have been undertaken by the CSIR–Central Institute of Mining and Fuel Research (CSIR–CIMFR) using small-diameter blast holes (approximately 32 mm) drilled in comparable rock formations. One such investigation was conducted in the Western Ghats along the Konkan Railway alignment, where controlled blast trials were carried out to excavate hard rock outcrops. The rock was weathered type highly jointed hard massive granite having density of 2555 kg/m3 and compressive and tensile strengths 72.80 and 13.36 MPa respectively. Ground vibration levels generated from these blasts were systematically monitored at varying distances from the blasting site. The statistical analyses of the vibration data obtained from these trial blasts has formed the basis on assessing the influence of blast-induced ground motions on nearby foothill structures in the present research.

It is well established that Peak Particle Velocity (PPV) is primarily governed by two variables, distance from the blast source (d) and the maximum explosive charge detonated per delay (Qmax) (Singh et al., 2020). Among these parameters, Qmax is generally considered the key factor in blast design for vibration control. To account for the combined influence of these parameters, the concept of Scaled Distance (SD) is introduced, as expressed in Eq. 1:

$$SD = \frac{d}{\sqrt{Q_{max}}} \tag{1}$$

In practice, the precise form of the PPV–SD correlation differs from site to site, but is usually expressed as a power-law relationship of the form:

$$PPV = a(SD)^{b} \tag{2}$$

Here the parameters a and b are site-specific empirical constants. The coefficient *a* represents the degree of seismic energy transmitted into the ground, which depends on factors such as confinement and the explosive characteristics, whereas *b* reflects the geological attenuation of vibrations with distance (Dowding, 1985). These constants are typically determined through regression analysis of multiple field measurements. By log-transforming Eq. 2, the relation takes the linear form shown in Eq. 3.

$$\log[PPV] = b \cdot \log[SD] + \log[a] \tag{3}$$

In this representation, the slope corresponds to site factor b, while the intercept is related to log[a]. A reliable regression line (high R^2, low error) enables prediction of PPV values for specified distances and charge weights (Birch & White, 2013).

Based on this established empirical approach, a site-specific predictive equation was derived from CSIR–CIMFR vibration data collected during the Konkan Railway blasting study. The regression analysis was performed using Blastware software (Instantel Inc., Canada), resulting in Eq. 4. The corresponding regression plot is illustrated in Figure 8.

$$V = 1003.1 \cdot \left[\frac{D}{\sqrt{Q_{max}}}\right]^{-1.278} \tag{4}$$

Coefficient of Determination = 0.844, Standard Deviation = 0.144.

In India, vibration safety limits are regulated by the Directorate General of Mines Safety (DGMS), Dhanbad, which specifies allowable PPV thresholds for different categories of structures, depending on their construction type, sensitivity, and functional importance. For instance, reinforced concrete industrial buildings are permitted relatively higher vibration limits, while heritage structures and multi-storey residential buildings, due to their vulnerability, are subject to much stricter permissible limits (refer to Table 4).

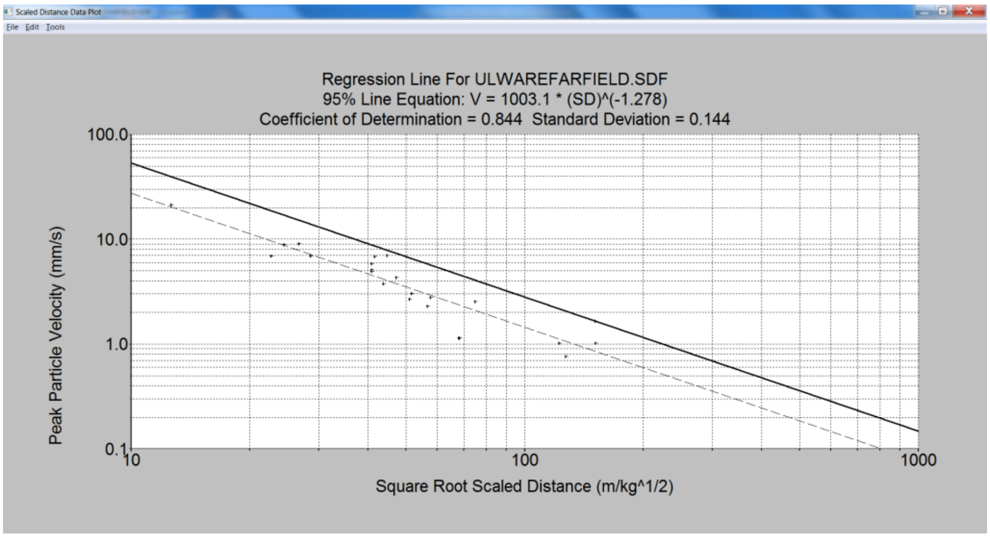

Figure 8. Plot of recorded ground vibration data with respect to scaled distance using Blastware software (Instantel Inc., Canada)

Table 4 DGMS ground vibration standards (DGMS, 1997)

Type of structure	Dominant excitation frequency < 8 Hz	8-25 Hz	>25 Hz
(A) Buildings/structures not belonging to the owner			
Domestic houses/structures (Kuchcha, brick & cement)	5 mm/s	10 mm/s	15 mm/s
Industrial buildings	10 mm/s	20 mm/s	25 mm/s
Objects of historical importance and sensitive structures	2 mm/s	5 mm/s	10 mm/s
(B) Buildings/structures belonging to owner with limited span of life			
Domestic houses/structures	10 mm/s	15 mm/s	25 mm/s
Industrial buildings	15 mm/s	25 mm/s	50 mm/s

With the help of established ground vibration predictor equation, the magnitudes of ground vibrations at different distances from the blasting face with varying quantities of maximum explosive charge per delay have been calculated and are given in Table 5. From the table, it can be found out that at a distance of 50 m from the blasting face, if the maximum charge per delay is 1.0 kg only, the PPV would be 6.8 mm/s. However, if we increase the distance to 70 m, the PPV with the same charge per delay would be 4.4 mm/s, but with the charge per delay of 1.5 kg and 2 kg, they will be 5.7 mm/s and 6.8 mm/s respectively. This indicates a direct relation of PPV with the distance and maximum explosive charge per delay used in a blast.

Table 5 Predicted magnitudes of ground vibrations at different distances with different Qmax values using the established predictor Equation 4

Distance [m]	Predicted values of ground vibration, PPV [mm/s]				
	Qmax - 1.0 kg	*Qmax - 1.5 kg*	*Qmax - 2.0 kg*	*Qmax - 2.5 kg*	*Qmax - 5.0 kg*
50	6.8	8.8	10.5	12.1	18.9
60	5.4	6.9	8.3	9.6	15.0
70	4.4	5.7	6.8	7.9	12.3
80	3.7	4.8	5.8	6.7	10.4
90	3.2	4.1	5.0	5.7	8.9
100	2.8	3.6	4.3	5.0	7.8
110	2.5	3.2	3.8	4.4	6.9
120	2.2	2.9	3.4	4.0	6.2
130	2.0	2.6	3.1	3.6	5.6
140	1.8	2.4	2.8	3.3	5.1
150	1.7	2.2	2.6	3.0	4.6

4.2.2 Blasting restricted zones for different Q_{max} and threshold PPV levels

Blasting restricted zones have been established for different maximum explosive charge per delays (Q_{max}) and for various vibration threshold levels recommended by the Regulatory Body in India. These zones, within which blasting activities are prohibited, are illustrated in Figure 9.

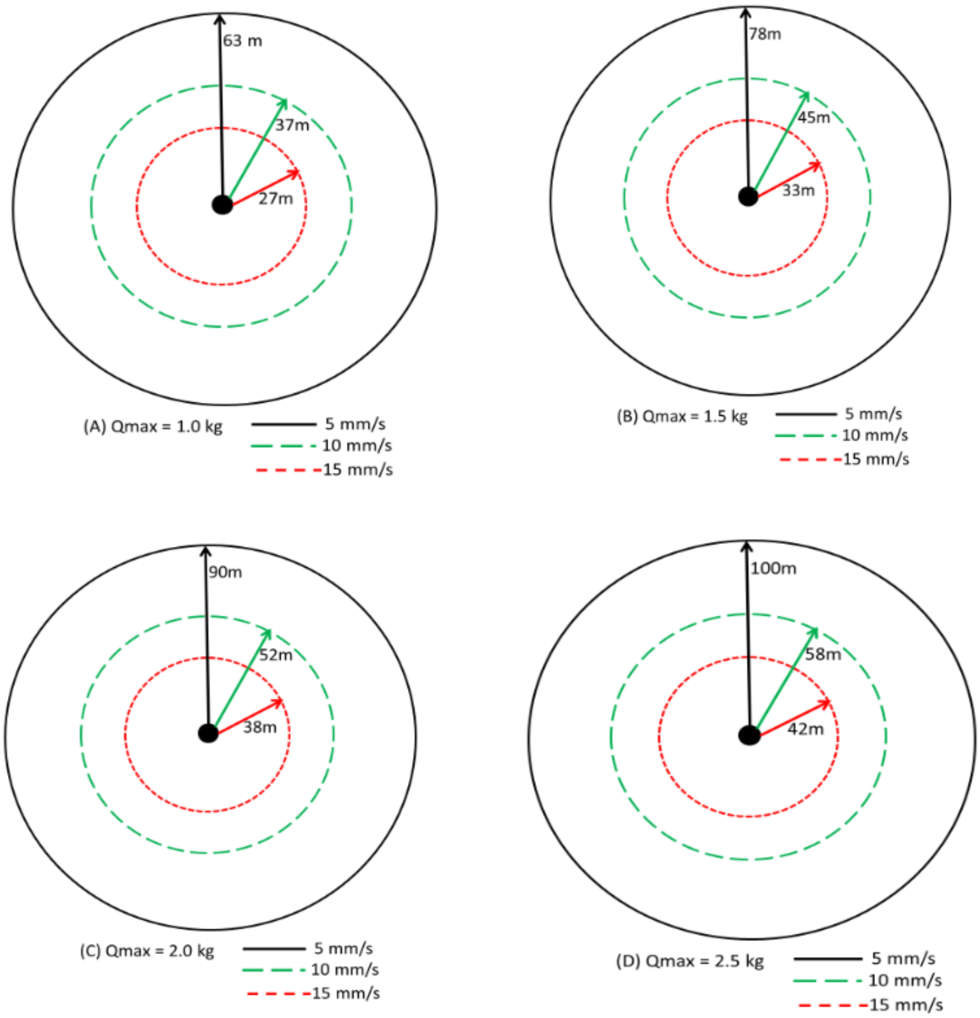

Figure 9. Blasting Restricted Zones for different threshold vibration levels (PPV) and maximum charge per delay (Q_{max})

It is evident from Figure 9 that when the threshold vibration level is set to the lowest value, that is, 5 mm/s, the blasting restricted zones, within which blasting activities cannot be performed, extend to 63 m, 78 m, 90 m, and 100 m for maximum charge per delay (Qmax) values of 1.0 kg, 1.5 kg, 2.0 kg, and 2.5 kg, respectively. Field observations at the GLSR construction site revealed that the nearest residential house is located approximately 70 m from the proposed GLSR boundary. Therefore, only a maximum charge per delay of 1.0 kg can be safely used to maintain vibration levels below 5 mm/s. Any charge per delay exceeding 1.0 kg would result in vibration magnitudes greater than 5 mm/s, as also indicated in Table 5.

The predicted ground vibration magnitudes at various distances from the blasting site, corresponding to different Qmax values, are presented in Table 4. It should be noted that the data used for these predictions were recorded at nearly the same elevation level as the blasting face. In the current scenario, however, controlled blasting for the GLSR construction will take place at the peak of Bharamtoli Hill, creating an elevation difference of more than 55 m between the blasting area and residential houses located at the foothill. Consequently, the actual vibration magnitudes resulting from controlled blasting operations are expected to be lower than those predicted by the established equation.

Based on the evaluation of ground vibration levels corresponding to various explosive charge per delay values, the delineation of blasting restricted zones for different PPV and Qmax levels, and the significant elevation difference between the GLSR site and nearby residential structures, it can be concluded that controlled blasting operations for hard rock excavation can be carried out safely without causing damage to surrounding houses and public infrastructure.

5 DEVELOPED CONTROLLED BLASTING METHODOLOGY AND BLASTING PARAMETERS

The methodology for hard rock excavation with controlled blasting technique should be as follows.

- Based on the capacity of the drilling machine and sensitiveness of the area, the complete excavation height varying between 696 - 687 m EL, (average 9 m) should be divided into six benches of 1.5 m each. The excavation should be carried out in a sequence from top to bottom. The entire width of the excavation of each layer/bench should be divided into many blasting patches depending on the number of the holes and location of the blasting face from the residential houses. The plan and sequence of excavation is shown in Figure 10.

- For excavation of rock in each layer, the controlled blasting should be conducted using the suggested design patterns given in Figure 11 and detailed in Table 6. With the help of suggested controlled blast design patterns, the throw of the blasted muck will be restricted within 5 m distance from the place of blasting.

- In order to prevent any flyrock during blasting operations, blasting mats of sufficient strength shall be placed over the entire blasting patch and on 1.5 m additional length.

- The final blasting should be carried out after taking proper shelter and giving sufficient warning to the surrounding inhabitant.

• Blast induced ground vibrations should be monitored at the nearest residential houses/structures situated at the foothill in order to assess the actual impacts of blasting and based on the results, the controlled blasting parameters should be modified.

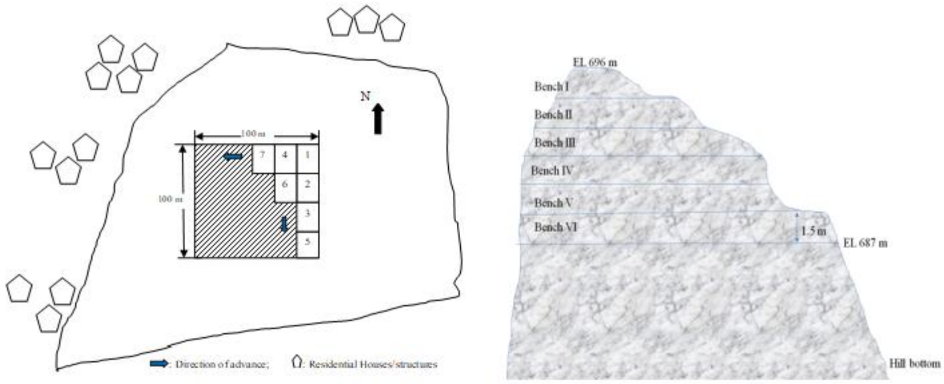

Figure 10. Plan and sequence of excavation of hard rock for conducting controlled blasting

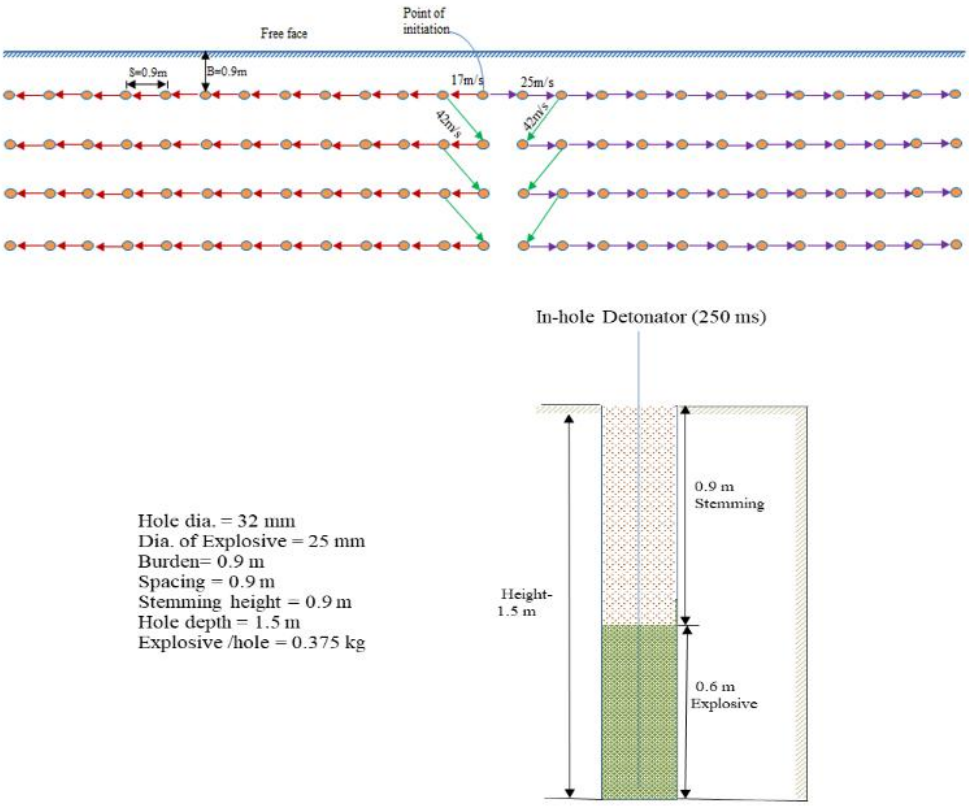

Figure 11. Layout of the suggested controlled blast design patterns

Table 6 Parameters of controlled blast design

Design parameter	value/range
Hole diameter	32 - 34 mm
Burden	0.8 - 0.9 m
Spacing	0.8 - 0.9 m
Depth of hole	1.5 m
No. of holes in a round of blast	50-180 (depending on site conditions and distance from the structures and will change after vibration and other blast results)
Type of explosive	Cartridge-type emulsion explosive (25 mm dia., 200 mm length, ~125 g per cartridge
Charge per hole	0.25 - 0.375 kg
Charge length	0.4 - 0.6 m
Max. charge per delay	1.0 - 2.5 kg (dependent on number of blast holes and distance to the nearest structure)
Total explosive quantity in the blasting round	12.50 - 67.50 kg (depending on site conditions, distance from structures and will change after vibration and other blast results)
Initiation system	Non-electric detonator system (Nonel) with in-hole detonators (DTH) of 250/275/450 ms and trunk-line detonators (TLD) of 17, 25 & 42 ms
Stemming length	0.9 - 1.1 m
Stemming material	Drill cuttings or crushed dust (size < 5 mm)

5.1 Protective arrangements

In order to avoid any flyrock from the blasting face, the entire blasting patch should be covered (muffled) before final firing after making surface connections of the charged holes. For this, heavy duty blasting mat built of rubber in sufficient quantities should be used. The entire blasting area should be covered using the blasting mats in addition to 1.5 m distance in all the sides. A photograph showing the muffling practice of a blasting patch is shown in Figure 12.

Figure 12. Muffling/covering of blasting patch using blasting mats

6 CONCLUSION

The comprehensive evaluation of various rock breakage techniques for timely completion of excavation works indicates that the use of controlled blasting methods with explosives is a feasible and safe option for the GLSR construction site. In contrast, non-explosive methods such as mechanical type hydraulic breakers, chemical expansion agents, plasma blasting, and thermal rock splitting are significantly slower and insufficient to meet the daily production targets within the project timeline.

The safety assessment of the controlled blasting method with explosives was conducted using data derived from a CSIR-CIMFR scientific study at a similar site in India. Based on this, an empirical equation was developed to predict ground vibrations by correlating the maximum explosive charge per delay with the distance of nearby structures from the blast point. Using this model, the safe explosive charge per delay (Qmax) was determined with a threshold Peak Particle Velocity (PPV) of 5 mm/s to ensure the safety of foothill structures.

The corresponding blasting exclusion zones for a 5 mm/s threshold PPV were established as 63 m, 78 m, 90 m, and 100 m for Qmax values of 1.0 kg, 1.5 kg, 2.0 kg, and 2.5 kg respectively. Since the nearest residential structure lies 70 m from the GLSR boundary, limiting Qmax to 1.0 kg ensures vibration levels remain below 5 mm/s. Additionally, because blasting will occur at the hilltop, an elevation difference of more than 55 m between the blast site and foothill residences will further reduce the vibration intensity.

Therefore, the detailed assessment confirms that controlled explosive blasting can be safely employed for hard rock excavation at the GLSR site, enabling timely completion of the project without jeopardizing the safety of nearby residential structures. The findings and methodology adopted in the present research work can be applicable to other similar cases where rock excavation is required in the urban vicinity.

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CONFLICTS OF INTEREST/COMPETING INTERESTS

The authors declare no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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