MINISTRY OF EDUCATION

PETROŞANI UNIVERSITY

DOCTORAL SCHOOL

DOCTORAL FIELD: INDUSTRIAL ENGINEERING

Eng. Bogdan GARALIU-BUȘOI

DOCTORAL THESIS

-SUMMARY-

ANALYSIS AND SAFETY ASSESSMENT OF EXPLOSIVE MATERIALS INTENDED FOR USE IN BLASTING OPERATIONS AT SURFACE MINING SITES

ANALIZA ȘI EVALUAREA SECURITĂȚII MATERIILOR EXPLOZIVE DESTINATE PENTRU REALIZAREA LUCRĂRILOR DE DEROCARE LA EXPLOATĂRILE MINIERE DE SUPRAFAȚĂ

Scientific Coordinator:

CSI PhD. habil eng. **DRAGOȘ GABRIEL VASILESCU**

PETROSANI

- 2024 -

CONTENTS

In today's era of technology and industry, surface mining is a critical pillar in meeting the global demand for natural resources. However, the rapid evolution of technology requires constant adaptation of the methods and processes used in this vital sector. In this context, the optimization of blasting technologies becomes crucial to ensure the efficiency, safety and sustainability of surface mining operations.

The thesis "***Analysis and safety assessment of explosive materials intended for use in blasting operations in surface mining sites***" addresses a current topic in the field of mining, seeking to contribute to the continuous evolution of the technologies used in this crucial sector, taking into account both economic, environmental and safety aspects.

This paper focuses on the concept of "Integrated Optimization of Blasting Technologies", addressing an innovative perspective based on computer simulations with state-of-the-art specialized equipment. These simulations can fundamentally transform the way we understand and manage blasting processes, with a significant impact on operational efficiency and environmental impact.

By integrating advanced computer simulation technologies, the paper aims to provide a broad perspective on traditional blasting methods in surface mining operations and highlight how new technologies can contribute to their optimization. Therefore, a number of advantages brought by computer simulations in the modelling and analysis of mining processes were highlighted, as well as how they can offer innovative solutions to current challenges.

By delving into the details of the state-of-the-art specialized equipment used in computer simulations, a complete picture of their potential in transforming surface mining operations will be provided. The thesis will also analyze relevant case studies and the results obtained in these simulations, highlighting the practical benefits of integrated optimization.

The motivation of the doctoral thesis is fundamental from several perspectives, including ensuring operational safety, environmental protection, economic efficiency and legal compliance. These aspects are detailed below:

Ensuring operational safety: it is essential to protect the life and health of workers involved in operations and neighboring communities. The analysis and evaluation of the safety of explosive materials contributes to the prevention of accidents and incidents, by identifying risks and implementing appropriate control measures.

Environmental protection: explosives must be used in a way that minimizes the negative impact on the environment. This includes reducing noise pollution and vibration, as well as preventing soil and water contamination. The assessment of explosive materials also includes aspects related to their environmental impact.

Economic efficiency: the correct and safe use of explosives ensures that derailment targets are achieved in a cost-effective manner. Careful evaluation can help optimize the consumption of explosive materials, thereby reducing operating costs.

Legal compliance: there are strict regulations on the use of explosives for industrial purposes, including mining. Safety analysis and assessment are necessary to ensure that all activities are carried out in accordance with applicable legislation, thus avoiding legal penalties and other consequences.

Risk management: Safety assessment includes the identification and analysis of potential risks associated with the handling, storage, and use of explosives. It enables the implementation of effective risk management strategies, such as staff education and training, as well as the development of emergency and incident response plans.

Improved work practices: through continuous analysis and security assessment, organizations can identify opportunities to improve work practices and the technologies used. It contributes to innovation and adaptation to changes in the industry.

In conclusion, the motivation for the analysis and evaluation of the safety of explosive materials in the context of blasting works at surface mining operations is complex and multidimensional, with the ultimate goal of ensuring a safe, efficient and sustainable operation.

The main objectives of the thesis

The analysis and assessment of the safety of explosives, in particular in the context of derocking works in surface mines, pursues several main objectives, which are essential to ensure efficient and safe operation. These objectives include:

Identification and risk assessment: One of the main objectives is to identify all potential risks associated with the handling, transport, storage and use of explosives. A detailed assessment of these risks is critical to understanding the potential impact on the safety of workers, nearby communities, and the environment.

Compliance with legislation and regulations: It is essential to ensure compliance with all relevant local, national, and international regulations. This objective includes compliance with safety rules, environmental standards and any other directives applicable to the management of explosives.

Implementation of best safety practices: Promoting and implementing best safety practices and standards in the handling of explosive materials, involves the use of appropriate protective equipment, proper training of personnel, and the application of standard operating procedures to minimize risks.

Optimizing the use of explosives: Determining the most efficient methods of using explosives to achieve derocking goals while reducing resource consumption and environmental impact.

Accident and incident prevention: By proactively identifying potential sources of error or failure, the goal is to prevent accidents and incidents before they occur, thus ensuring a safe working environment.

Emergency management and response: Develop and implement effective emergency response plans that allow for rapid and coordinated responses to unexpected incidents, minimizing the impact on staff, community and environmental safety.

These main objectives underline the complex and multidisciplinary approach needed to ensure the safe and responsible use of explosives in the mining industry, contributing to the protection of workers, neighboring communities and the environment.

Structure of the thesis and some contributions

From a structural point of view, the thesis contains an introductory chapter with specific topics and 6 chapters of content, to which is added a final chapter of Final Conclusions and personal contributions, for a total of 251 pages, of which 185 pages represent the thesis itself and 4 pages represent **the Bibliography** which has a number of 74 bibliographic notes and **The Specialized Annexes** which contribute to a better understanding of the thesis and its objectives.

The doctoral thesis entitled ***Analysis and safety assessment of explosive materials intended for use in blasting operations at surface mining sites*** is structured in 8 chapters.

In the **first chapter**, called *Introduction,* the general considerations, the main and specific objectives, the motivation of the thesis and a brief summary of the work are presented.

Chapter 2, *Study of the Evolving Regulatory Framework in the Field of Explosive Materials*, addresses the evolution of regulations on explosive materials, with a focus on European and national legislation, and the requirements for personnel working with such materials.

The European Union Directive 2014/28/EU (explosives for civil use) harmonizes the rules and standards relating to the placing on the market and control of explosives for civil use in the EU.

The main objective is to ensure the free movement of these products while maintaining a high level of protection of public health and safety. Law No. 126 / 1995, in Romania, establishes the legal framework for the management, use, storage, transport and marketing of explosive materials. Personnel carrying out operations with explosive materials must be specially trained and authorized.

EU regulations, including those adopted by Romania, require the implementation of a system for the unique identification and traceability of explosives for civil use. It allows for the monitoring and control of explosives distribution, helping to prevent illegal use and ensure public safety.

The chapter concludes that the implementation of national and European legislation in the explosives sector has led to high standards of safety and compliance. Law No 126/1995 and other relevant regulations ensure an adequate regulatory framework for the control of the production, possession, marketing, transport and use of explosive materials, contributing to national security and preventing the illegal use of explosives. This summary provides an overview of the legislative context and essential requirements for the management of explosive materials at European and national level, emphasizing the importance of compliance and safety in the handling of such materials.

Aspects related to the *Critical Analysis of Blasting Technologies for the Excavation with Explosives of Useful Mineral Substances from Surface Mining Operations* are highlighted in **Chapter 3**, where the focus is on the critical analysis of blasting technologies used for the excavation with explosives of useful mineral substances from surface mining operations. Surface mining, also known as open-pit mining, involves the extraction of minerals and metals from the Earth's surface. It is used when deposits are near the surface and economically feasible to exploit. The main methods include quarries, open-pit mines, strip mining, and dissolution mining. Blasting work is essential for rock fragmentation in surface mining and other fields. The choice of the appropriate technology depends on geological conditions and rock characteristics, ensuring

work safety and protection against explosion-related hazards. This synthesis provides an overview of the context, advantages, and disadvantages of surface mining, critical blasting technologies used, and conclusions regarding the efficiency and safety of these methods.

In **Chapter 4**, titled *Contributions to the Assessment of the Seismic Effect Generated by Blasting Works in Surface Mining Operations*, the issue of seismic effects generated by blasting works in surface mining is addressed. These works are essential for rock fragmentation but have a significant impact on the surrounding environment, nearby buildings, and the safety of personnel. Therefore, evaluating and controlling seismic effects are crucial for minimizing risks and optimizing mining processes.

Overall, the chapter provides a detailed analysis of the seismic effects generated by blasting works, emphasizing the mechanisms of seismic wave generation and propagation, methods of measurement and evaluation, and the importance of implementing rigorous procedures to minimize environmental and safety impacts.

Chapter 5 - *Risk and Environmental Impact Assessment* presents a series of significant risks classified into several categories, based on their nature and source. These include risks associated with the use of explosives (uncontrolled detonations, production of flying fragments, air and water pollution), safety measures (procedures for handling and storing explosives, safety distances, personal protective equipment), as well as the environmental impact, including the assessment of the impact of vibrations and seismic waves on nearby structures and ecosystems.

Chapter 6 - *Contributions to the Integrated Optimization of Blasting Technologies Used in Surface Mining Operations Based on Computer Simulations Conducted with State-of-the-Art Specialized Equipment*, highlights the study of computer simulation and modeling methods for blasting processes specific to surface mining operations, as well as the analysis and evaluation of the results obtained from these computer simulations with a focus on increasing the efficiency of mining operations carried out in surface mining.

In **Chapter 7** - *Contributions to the Evaluation of the Seismic Effect Generated by Blasting at the Level of Certain Mining Operators*, the evaluation of the seismic action of blasting works executed in marble quarries is presented, with the aim of protecting the deposit from the effects of these works, as well as the evaluation of the seismic effect of blasting works executed in basalt rock quarries.

Chapter 8, titled *Final Conclusions and Personal Contributions*, highlights the contributions made to the development of the infrastructure regarding the integrated optimization of blasting technologies used in surface mining operations based on computer simulations conducted with state-of-the-art specialized equipment, as well as the manner of implementation and utilization of the research results undertaken, both currently and in the future.

In this doctoral thesis, a comprehensive and detailed analysis of critical aspects related to the use of explosive materials in surface mining operations was conducted, with a particular focus on the integrated optimization of blasting technologies. The resulting conclusions emphasize the importance and significant impact of this field on operational safety, economic efficiency, and environmental protection.

A central aspect of the thesis was the analysis of blasting technologies and their optimization methods through the use of advanced computer simulations. The studies demonstrated that the integration of modern technologies and the use of state-of-the-art simulation equipment can bring significant improvements in the

efficiency of blasting processes, thereby reducing resource consumption and environmental impact. Computer simulations allow for precise modeling and rigorous evaluation of explosion effects, contributing to the optimization of operational parameters and the minimization of associated risks.

The analysis of explosive material security revealed the importance of implementing strict safety and monitoring measures at all stages of handling, transportation, and use of explosives. Detailed risk assessments and the implementation of rigorous control procedures contribute to the prevention of accidents and the protection of the lives and health of workers, as well as neighboring communities. Environmental protection is ensured by reducing the impact of vibrations and noise pollution, as well as preventing soil and water contamination.

The thesis underscores the necessity of complying with strict regulations imposed by national and European legislation regarding the use of explosive materials. Compliance with these regulations ensures not only the legality of operations but also a high level of safety and environmental protection. The study of the legislative framework highlighted the importance of implementing a system of unique identification and traceability of explosives, contributing to the prevention of illegal use and ensuring public security.

Another essential aspect addressed was the evaluation of the seismic effect generated by blasting works. Detailed measurements of particle oscillations and the analysis of seismic parameters allowed for the establishment of maximum quantities of explosives that can be used without exceeding the permissible oscillation speed limits. The implementation of rigorous measurement and evaluation procedures for seismic effects is crucial for minimizing the impact on structures and the surrounding environment. The results obtained demonstrate that the level of seismicity generated is acceptable but requires continuous monitoring to ensure long-term safety.

Key Results of the Chapters

Chapter 2

This work led to a comprehensive literature review on the legislative aspects concerning the regulation of civil-use explosives, specific terminology in the field of civil-use explosives, and the applicable requirements for adhering to safety measures and preventing undesirable situations when working with civil-use explosives.

The legislative aspects implemented at the national level were analyzed and documented, aligning with European standards through Law 126/1995 on the regulation of explosive materials and HG207/2005, which transposes the requirements of the Council Directive 93/15/EEC of 5 April 1993 on the harmonization of provisions relating to the placing on the market and supervision of explosives for civil uses.

The transportation and destruction of civil-use explosives were addressed at the end of the report, highlighting the technical and regulatory aspects that govern the legal transportation of explosives, considering the transport category, type of substance, packaging/classification group/UN number, and the maximum total quantity per transport unit. Technical and procedural aspects regarding the destruction of unusable civil-use explosives due to deterioration and those resulting from misfires were also highlighted.

Both security and performance requirements were emphasized, including the harmonized reference framework and the testing methods used to verify the technical conformity for safe use in specific activities.

The completion of this report's objective led to the establishment of specific requirements, the development of control procedures, and the presentation of necessary IT and specialized software equipment and hardware tracking devices.

A modular, harmonized system for the unique identification and traceability of civil-use explosives, such as the TTE (Tracking and Tracing of Explosives) system, enables the implementation of the requirements of European Union Directive 2008/43/EC and its amendments by Directive 2012/4/EU, ensuring the safe and secure movement of civil-use explosives and combating potential terrorist actions, while also providing relevant and reliable information to the authorities.

As of 5 April 2015, all economic operators in the explosives sector are required to establish a data collection system for explosives, including the unique identification marking throughout the supply chain and their lifespan.

The harmonized electronic system for the unique identification and traceability of civil-use explosives represents a monitoring tool in compliance with the European directive requirements, providing an integrated, easy, safe, and rapid means of control throughout the entire logistics flow of these explosive products, from manufacturers, transporters, and distributors to users.

To ensure the proper use of the unique identification and traceability system for civil-use explosives, in compliance with legal requirements and the quality system implemented at an economic operator level, the control procedure, coded PC-Explosive Traceability 01, was developed.

Chapter 3

Blasting work is an extensive and frequently used method for rock fragmentation in various fields such as construction, roads, leveling, and others. Various blasting technologies are employed in these works, including mine boreholes, well boreholes, and mining galleries. The choice of the appropriate technique depends on geological conditions, rock characteristics, work safety, and protection of objectives and personnel against explosion-related hazards.

Different blasting techniques, such as concentrated or elongated charges, are adapted based on the blasting purpose and specific working conditions. The impact of the explosion on the environment depends on the charge size and distance to the free surface. The explosion action index (n) classifies blasting according to how the environment is affected, ranging from throw blasting to camouflet blasting.

The main blasting techniques used in the industry are presented, such as those for oversized blocks and specific techniques for mine or well boreholes. Details regarding the placement of boreholes, specific explosive consumption, and blasting schemes are highlighted in the context of various situations and working conditions.

Chapter 4

The research conducted in this chapter leads to the following conclusions and proposals:

The geological boundary correlation takes on different aspects from one type of geophysical information to another. The concept of an isolated geological body can often introduce a formal correlation, and geophysical simulation modeling can give it greater consistency, bringing the interpretation solution closer to geological reality.

Numerous diverse factors influence the analysis of the seismic wave propagation mechanism, creating difficulties in solving this problem concerning the modeling of the "propagation medium." An acceptable analytical solution can be identified by accepting simplifying assumptions and considering the four fundamental principles of wave propagation while neglecting elements whose influence on the overall phenomenon can be considered secondary. Under these conditions, the "propagation medium" is reduced to a perfectly elastic, homogeneous, isotropic, continuous, and uniform model.

Seismic waves generated by the energy released at the focus are transmitted through the propagation medium following extremely complex reflection and refraction phenomena due to the heterogeneity and discontinuity of the layers they traverse. Local geological conditions characteristic of a specific site have a decisive influence on modifying seismic effects.

Elastic waves generated by the energy release at the focus during a seismic event propagate radially in all directions. Two types of waves can be distinguished:

Volume waves: P-waves (primary waves), whose displacement is achieved through successive compressions and dilations of the medium in their propagation direction, comparable to sound waves; S-waves (secondary waves), which define motion parameters and produce the most significant dynamic effects on surface structures, are shear waves moving through perpendicular particle vibrations in their propagation direction.

Surface waves (arising from the repeated reflection of volume waves in geological deposits near the Earth's surface): Love waves, which move similarly to S-waves but propagate horizontally parallel to the Earth's surface; Rayleigh waves, which have an orbital movement in a vertical plane in the propagation direction.

To get a realistic picture, pre-activity evaluation methods for blasting with civil-use explosives must consider as much information as possible regarding blasting conditions, explosive type, detonation technique, characteristics of the medium in which the explosive detonates, and the medium generating seismic waves. The seismic effect evaluation method uses "particle oscillation velocity" as an evaluation parameter, with the accepted level in NSPM code 71 (repealed) being a maximum of 0.5 cm/s for repeated blasts.

Evaluations highlighted differences in approach regarding the accepted level considered non-dangerous for certain construction types. Evaluation tools use particle velocity measured over frequency intervals on three components (radial, vertical, transverse). Using "oscillation velocity" versus "oscillation frequency" as a reference parameter enables an appropriate evaluation without being overly restrictive for blasting conditions, allowing higher oscillation velocity values (>0.5 cm/s) if measured in 20-100 Hz frequency intervals.

To ensure the safety and integrity of objectives in the blast influence zone, the quarry owner should monitor each blast's seismicity, enabling timely intervention by reconsidering quantitative/geometric blasting parameters, reducing disturbance levels for nearby populations.

Chapter 5

Evaluating and managing the impact of vibrations and seismic waves is essential for protecting the environment during the use of explosives. By implementing rigorous evaluation practices, continuous monitoring, and adopting impact reduction measures, risks can be minimized, and the conservation of sensitive structures and ecosystems can be ensured. Collaboration among environmental specialists, engineers, and authorities is crucial for developing and applying effective environmental protection strategies.

Chapter 6

This chapter successfully demonstrated the effectiveness of integrating advanced computer simulation and modeling techniques in surface mining blasting processes. Key findings include:

- Increased predictive accuracy of explosion results, optimized use of explosives, and improved safety measures.
- Simulation tools like BlastManager, ShapeMetriX3D, JMX Analyst, and BMX BlastPlanner enabled detailed and precise modeling of blasting processes. These technologies allowed the evaluation and optimization of operational parameters, reducing resource consumption and minimizing environmental impact.
- Applying finite element methods (FEM) and discrete element methods (DEM), along with machine learning algorithms, revolutionized the ability to predict and optimize blasting operations, shifting from traditional methods to a more sophisticated data-based approach.
- These findings represent a substantial shift towards more sustainable, safer, and cost-effective mining practices. By enabling more precise and efficient blasting operations, these technologies contribute to better resource management, reduced environmental footprint, and increased compliance with regulations. This aligns with broader goals of enhancing operational sustainability and minimizing the ecological impact of mining activities.

Chapter 7

This chapter offers essential conclusions regarding the impact of blasting works on the environment and the safety of structures in mining operations. Blasting in marble and basalt quarries generates seismic waves affecting structures near the mining site. Research established correlations between particle oscillation speeds and permissible seismic effects, determining maximum permissible speeds for different environments.

The propagation of seismic waves and their effects are influenced by the elastic properties of rocks. In compact environments like underground excavations, maximum permissible oscillation speeds are imposed to prevent residual deformations that could damage structural integrity. Residual deformations resulting from repeated explosion seismic effects can compromise structural stability.

The multiple effects of explosions on the environment manifest through relative deformations exceeding permissible elastic values, posing destruction risks to structural stability.

Seismic wave parameters were measured and recorded to evaluate the impact of blasting works.

Studies included detailed measurements of particle oscillations and analysis of results to determine the maximum permissible dynamic parameters of explosions.

Seismic effect evaluations established the maximum quantities of explosives that can be used without exceeding permissible oscillation speed limits.

Explosive quantities per delay step were determined by applying a function to reduce the seismic effect.

Implementing rigorous measurement and evaluation procedures for seismic effects optimizes blasting works and minimizes environmental and structural impact.

The work reveals the necessity of continuing measurements and periodic seismic effect reevaluations to adapt procedures to the dynamic conditions of mining operations.

The results obtained demonstrate that the level of seismicity generated is acceptable for given conditions but requires continuous monitoring to ensure long-term safety.

These conclusions underscore the importance of evaluating and controlling seismic effects in mining operations, highlighting the necessary measures for protecting the environment and surrounding structures.

General Conclusions

Thus, the thesis's conclusions covered a wide range of essential aspects of using explosives in mining operations, emphasizing the need for an integrated approach to ensure the safety, efficiency, and sustainability of mining operations. These findings and recommendations provide a solid framework for continuously improving the technologies and practices used in this crucial field.

In conclusion, the work highlights the complexity and multidimensional nature of surface mining operations, emphasizing the need for an integrated and innovative approach to ensure the efficiency, safety, and sustainability of these operations. The contributions made by this research provide a solid foundation for developing and implementing advanced technologies that meet the current and future demands of the mining industry.

The work underscores the necessity of continuing research in optimizing blasting technologies, considering rapid technological advancements and increasingly stringent safety and environmental protection requirements.

Future research directions focus on continuing studies on operational parameter optimization, developing new technologies and simulation methods, and constantly adapting to technological evolutions and environmental requirements. These include:

- Developing more advanced and integrated simulation models for more precise prediction and control of blasting effects.
- Implementing real-time monitoring technologies for blasting parameters and seismic effects to dynamically and adaptively optimize processes.
- Expanding studies on the ecological impact of explosive materials and developing less polluting and more energy-efficient alternatives.
- Developing methods to incorporate real-time data into simulations to adapt blasting operations to changing conditions.
- Expanding data sets to include a wider range of geological conditions, improving model generalization.

- Exploring more sophisticated machine learning techniques, such as deep learning and reinforcement learning, for enhanced predictive capabilities.
- Developing models that can simultaneously predict the environmental impact of blasting works, such as vibrations, noise, and dust dispersion.
- Conducting detailed economic analyses of implementing advanced simulation technologies in mining operations to justify investments from a cost-benefit perspective.
- Developing efficient training programs and implementation strategies to ensure mining personnel can adequately use these advanced technologies.

In the end, the thesis significantly advances knowledge in the security and optimization of explosive materials usage in surface mining operations, offering practical and innovative solutions for current and future challenges in this essential sector.