SEISMIC EFFECTS OF BLASTING AND THEIR INFLUENCE ON THE STABILITY OF SLOPES IN SURFACE MINES

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ABSTRACT

Blasting represents a fundamental technological operation in the surface exploitation of mineral resources; however, it also generates dynamic loads that can affect on the stability of bench slopes. During mass blasting operations in open pit mines, seismic vibrations are generated, leading to damage in the rock mass and the formation of secondary fractures that propagate into the depth of the rock massif. This process disturbs the equilibrium state of the rock mass and consequently affects the bench slopes. This paper analyzes the seismic effects of explosive blasting and their influence on the geomechanical stability of slopes in an open pit mines.

Keywords: blasting, seismic effects, seismic waves, slope stability, open pit mines.

INTRODUSTION

Surface mining of mineral resources is based on the systematic excavation of rock masses through the use of explosives. The increasing number of low-grade deposits, along with the growing demand for useful mineral resources, necessitates the use of larger quantities of explosives during blasting operations. As a rule, this approach yields greater economic efficiency compared to frequent blasting with smaller explosive charges.

However, blasting with large quantities of explosives generates stronger seismic vibrations, which may cause damage to mining facilities and affect the stability of bench slopes.

During blasting, in the initial phase, the explosive is transformed into a highly compressed gaseous state, followed by the expansion of these gases, during which potential energy is converted into mechanical work. This energy crushes the rock mass near the blast site, creates cracks and permanent deformations at greater distances, and further away it manifests as elastic deformation.

Seismic waves propagate through the medium as a result of this deformation transfer, causing oscillations of the ground and of all structures located on it.

The seismic oscillations induced by blasting are quite similar to those generated by earthquakes; therefore, many principles from seismology, as well as appropriate measuring instruments, can be applied for their analysis. The primary difference between these two phenomena lies in the duration and period of oscillations. In blasting, the duration of oscillations is significantly shorter, typically ranging from 0.004 to 0.25 seconds. There is also a difference in the range of represented frequencies, i.e. significantly a wider spectrum of frequencies is represented in the records of oscillations due to earthquakes in relation with blasting. In figure 1, three records of oscillations caused by blasting, nuclear explosion and earthquake are presented.

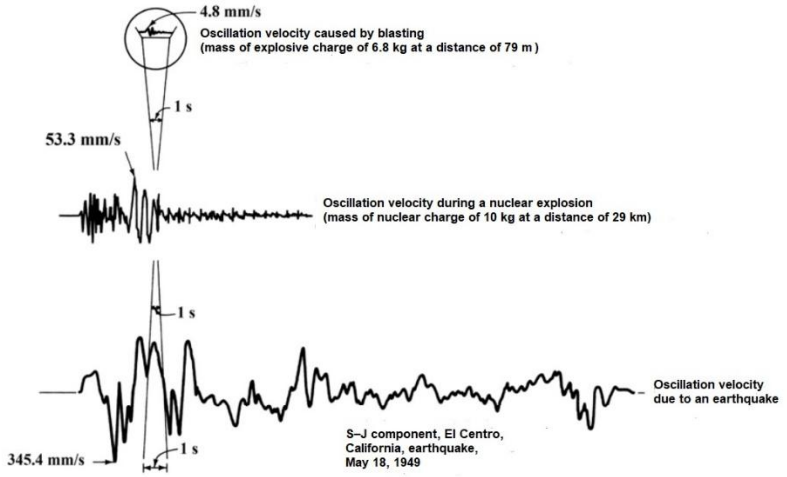


Figure 1. Comparison of records of oscillation velocities from blasting, nuclear explosion and earthquake [1] (Dowding, 1996)

The seismic effects of blasting are influenced by several factors, the most important being: the quantity of explosives used, the distance from the blast site, the type of explosive, the geometric distribution of energy within the blast field, the initiation method, geological and structural characteristics of the ground, and the condition of nearby structures.

Methods for monitoring the impact of blasting on slope stability can be classified into: simple methods, geodetic methods, and geophysical methods.

Simple methods involve visual observation of slopes in open pit mines, photographic documentation before and after blasting, high-speed camera recording immediately prior to blasting, inspection of rock masses along final contours through boreholes using optical instruments, and analysis of slope disturbance through drilling rate and water displacement from boreholes and fractures.

Geodetic methods enable the determination of deformations in working and final bench slopes during blasting. Bench profiles are established along the final contours of the open pit, both at the surface and at depth, where reference points (benchmarks) are installed. Using geodetic instruments, displacements are recorded and monitored.

Geophysical methods register oscillations of the rock mass in working and final slopes by monitoring particle velocity and acceleration within the ground. Stresses generated in the rock mass are measured using piezoelectric and pressure sensors installed in boreholes filled with water, gypsum, or other materials. In addition, acoustic methods are used to determine the degree of disturbance in working and final slopes. These methods evaluate the velocity of wave propagation through the rock mass and assess its degree of fracturing.

METHODOLOGY

The research presented in this paper is based on a combined approach that includes theoretical analysis, empirical relationships, and modern monitoring methods for seismic effects induced by explosive blasting in surface mines.

In the first phase, an analysis of the physical processes occurring during explosive detonation was conducted, with particular emphasis on the generation and propagation of seismic waves through the rock mass. Key factors influencing the intensity of seismic effects were examined, including the explosive charge, the distance from the blasting site, the geomechanical properties of the rock mass, and the initiation method.

In the second phase, empirical mathematical models were applied for quantitative assessment of seismic parameters, with special focus on:

- the relationship between oscillation amplitude, explosive charge, and distance;
- the Sadowski equation for determining the peak particle velocity (PPV);
- the evaluation of elastic and plastic deformation zones within the rock mass.

In the third phase, the influence of seismic waves on the stability of bench slopes was analyzed by defining critical values of particle velocity and correlating them with the degree of damage (cracking, sliding, and rockfall occurrences).

Additionally, several monitoring methods were applied to assess slope conditions:

- visual and observational methods,
- geodetic methods for displacement measurements,
- geophysical methods for recording vibrations and stresses,
- acoustic methods for evaluating rock mass fracturing.

Within the framework of modern research, the application of an alternative monitoring system based on audio recorders and DAQ technology was also analyzed. This system enables real-time acquisition and processing of seismic data. It includes the use of geophones, high-resolution analog-to-digital conversion, and a mobile platform suitable for field deployment.

By integrating theoretical models with experimental data, a comprehensive assessment of the dynamic impact of blasting on slope stability in surface mines was achieved.

INDUCED SEISMICITY DURING MINING

During blasting, shock elastic-plastic and elastic waves occur in rock masses. In the immediate vicinity of the borehole, during the blasting itself, the rock mass is destroyed. The distance at which elastic waves occur is given by the following empirical formula:

$$r = 0.12\sqrt[3]{Q}$$

Where:
r- distance where elastic deformations appear [m]
Q- explosive charge [kg]

In engineering practice, particularly from the perspective of blast-induced seismicity, special attention is given to the zone of elastic deformation, i.e., the zone through which seismic waves propagate. Compared to the crushing zone and the zone of permanent (plastic) deformations, this zone is significantly larger and may encompass a substantial volume of the rock mass.

Seismic waves generated during blasting, especially in cases of inadequately designed charging and initiation patterns, can be detected at distances of several tens of kilometers from the detonation site. This creates a potential risk front for the wider surroundings, including structures, infrastructure, bench slopes, and natural geostructures.

The relationship between the oscillation amplitude, the explosive charge per delay, and the distance of the observation point from the blast field is given by the following equation

:

$$A = 392.3\sqrt[3]{0.45 \cdot Q^2} \cdot (0.07e^{-0.00045r} + 0.001)$$

Where:

A- displacement amplitude [cm]
Q- explosive charge [kg]
r- distance from the blastingfield [m]

This equation is used for distance from 150 to 2000 meters.
The speed of oscillations at the observation site is given by the following Sadowskki formula:

$$V = K(\frac{\sqrt[3]{Q})^n}{r})$$

Where:

V- maximim particle oscillation speed [cm/s],
r- distance from the observation point to the blastingfield [m],
Q- amount of explosive charge [kg],
K- seismoacoustic constant determined by field measurement,
n- exponent determined by soil characteristics and blasting conditions and determined by field measurement.

The application of this dependence allows for a quantitative assessment of the seismic action of blasting and provides a basis for analyzing the dynamic stability of the slopes of open pit mines.

INFLUENCE OF SEISMIC WAVES ON THE STABILITY OF BENCH SLOPES IN OPEN PIT MINES

The propagation of seismic waves along bench slopes in open pit mines is fundamentally similar to their propagation through a rock mass with a horizontal free surface. However, due to the presence of an inclined free surface, certain additional physical phenomena occur, which significantly influence the attenuation and distribution of seismic energy.

In contrast to horizontally layered media, the existence of a slope introduces complex wave interactions, including reflection, refraction, diffraction, and mode conversion at the free surface. These processes lead to additional scattering and partial absorption of seismic energy, resulting in increased attenuation of vibration amplitudes along the slope. Furthermore, geometric spreading of waves becomes more pronounced due to the irregular topography, which additionally contributes to energy dissipation.

It is also important to note that local geological and structural conditions—such as discontinuities, joints, bedding planes, and faults—can further amplify or dampen seismic wave propagation. In some cases, these discontinuities may act as waveguides, facilitating the transmission of energy over greater distances, while in other cases they contribute to rapid attenuation. The particle velocity at the surface of a bench slope, which represents one of the most important parameters for evaluating the impact of blasting on slope stability, can be determined using the well-known Sadowski empirical relationship. This relationship establishes a correlation between the particle velocity, the explosive charge, and the distance from the detonation point, while also implicitly accounting for geological conditions.

For distance from 5 to 70 m from the blasting site and millisecond delay intervals of 15-50 ms, the following expression can be applied:

$$\boldsymbol{v} = \frac{\boldsymbol{k_1}}{\sqrt[3]{\boldsymbol{n}}} \cdot \sqrt{\frac{\boldsymbol{Q}}{\boldsymbol{L}}} \cdot \frac{\boldsymbol{e^{-0.032}}}{\boldsymbol{r}} (\frac{\boldsymbol{cm}}{\boldsymbol{s}})$$

Where:

κ_1- proportionality coefficient, which depends on rock properties; for hard rocks(f>14), it typically ranges from 300-700,

n- number of delay intervals in millisecond blasting,

Q- explosive charge per block (kg),

L- length of the blasted block (m) and

e- base of the natural logarithm

The value of particle velocity is directly related to the intensity of seismic loading acting on the slope. Higher velocities indicate stronger dynamic effects, which may lead to the initiation or propagation of fractures, reduction of shear strength along discontinuities, and ultimately to slope instability.

The relationship between particle oscillation, stress induced by seismic waves, and deformation of bench slopes can be more comprehensively expressed as a functional dependence on several key parameters

$$v = f(Q, r, C, \gamma)$$

Where:

C- velocity of wave propagation through the rock mass

γ- density of the rock (g/cm^3)

These parameters together define the acoustic impedance of the medium, which plays a crucial role in the transmission and reflection of seismic energy. A higher acoustic impedance generally results in more efficient transmission of seismic waves, thereby increasing their potencial impact on slope stability.

Numeous studies have shown that the extent of demage within the rock mass, particularly in working and final bench slopes, is strongly dependent on the explosive charge and the distance from the blast. This relationship is commonly expressed through empirical formulas derived from field observation. One such widely used expression is:

$$r_z = k_p \sqrt[3]{Q}$$

r_z- distance from the zone of complete crushing to the farthest extent of deep cracking (m)

k_p- proportionality coefficient, depent on geological conditions and blasting parameters

Q- explosive charge mass per delay (kg), considering one borehole in single row blasting and two boreholes in doble-row blasting.

Table 1.

Degree of rock fragility	Rocks		
	Easily blastable	Moderately blastable	Difficult to blast
Soft	2.0-1.0	1.2-0.6	0.7-0.2
Medium soft	1.3-0.8	0,7-0.2	0.25-0
Tough (hard)	0.8-0.6	0.4-0.1	0.1-0

According to N.I. Okhramenku, the size of the deep crack zone depends on the mass of the explosive charge per unit length of the block neing mined and the deceleration interval.

$$r_z = k_p \sqrt[3]{\frac{Q}{L}}$$

Where:

k_p- proportionality coefficient
Q- mass of explosive charge in the block (kg) and
L- length of the block being blasting (m).

Table 2.

Number of rows of boreholes	Proportionality coefficient depending on the deceleration interval					
	10	20	30	40	50	60
2	1.5	1.4	1.3	1.25	1.1	1.0
3	-	1.5	1.4	1.35	1.2	1.1
4	-	2.0	1.8	1.6	1.4	1.2

In existing empirical models, bench deformations are most often not directly correlated with the parameters of seismic waves. However, if the analysis incorporates the particle velocity at the slope surface, the acoustic properties of the rock mass, and the critical stress levels at which deformations occur, it becomes possible to establish a direct functional relationship between the parameters of the seismic wave and the degree of deformation of bench slopes in open pit mines.

By integrating these parameters, a more quantitative assessment of the dynamic impact of blasting can be achieved. In this context, slope deformations can be analyzed as a function of the intensity of ground motion, i.e., as a function of the amplitude and energy characteristics of seismic waves. The dependence of slope deformations on the degree of seismic excitation is shown in the following table no.3.

Table 3. Dependence of slope deformations on the degree of seismic excitation [2] (Mironov, 1973)

Degree of seismic excitation	Particle velocity cm/s	Possible consequences
6	2.7-5.5	Cracks in wet rocks up to 10 cm wide; isolated cases of sliding and rockfall from bench slopes
7	5.5-11.0	Minor cracks on dry slopes; numerous cracks on water-saturated surfaces; occasional sliding and rockfall from benches
8	11.0-22.0	Large number of cracks on bench slopes and in loose deposits; possible sliding and detachment of smaller rock fragments
9	22.0-42.0	Crack widths on bench slopes and in weak rocks reach up to 10 cm; possible sliding of isolated rock masses
10	42.0-75.0	In loose and highly saturated rocks, crack widths reach several decimeters; sliding in weak zones; possible rockfalls on steep bench sections along bedding planes
11	75.0-150.0	Formation of numerous cracks and fissures; vertical displacement of rock masses along bedding planes; rolling, sliding, and rockfall from bench slopes
12	>150 cm/s	Loss of integrity of hard rock masses in blocks and bench slopes; significant rockfall and large-scale sliding of slope sections

By knowing the dynamic limit values of the resistance of the rock mass under conditions of deep crack and fissure formation, it is possible to determine the critical particle velocity at which corresponding stresses are generated. The critical velocity is determined based on an appropriate analytical relationship that correlates the particle velocity with the dynamic strength characteristics and acoustic properties of the rock mass.

$$v_{kr} = \frac{2k_d \cdot \sigma_{pst}}{\gamma \cdot C}, cm/s$$

Where is:

K_d – coefficient of dynamic resitance,

Σ_{pst}- static stress limit in the rock mass (dN/cm^2),

γ- bulk density of the medium (g/cm^3)

The critical velocity represents the threshold value of the parameter (PPV) at which dynamic stress exceeds the elastic limit of the rock mass and transitions into the domain of plastic damage. Its determination enables a direct correlation between the parameters of the seismic wave and the degree of deformation of the bench slope,

ASSESSMENT OF THE EFFECT OF BLASTING ON BENCH SLOPES

The quantitative assessment of the influence of blasting on the stability of slopes in open pit mines can be carried out based on the intensity of seismic vibrations induced by blasting, under conditions that ensure the stability of working bench slopes.

Table 4. [3]

Degree of seismic excitation	5	6	7	8	9	10	11	12
Speed of oscilation	1.7-2.7	2.7=5.5	5.5-11	11-22	22-42	42-75	75-150	>150

The particle velocity at the surface of the slope mass is taken as the criterion for intensity. Based on equation (1), a graph of the intensity zone can be constructed as a function of explosive consumption, for rocks with a given bulk density and velocity of sound propagation in air.

CURRENT RESEARCH

Traditionally, seismometers and accelerometers have been widely used for monitoring seismic effects induced by blasting operations. Although these instruments provide reliable and valuable data regarding the characteristics of blasting events, they often offer limited insight into the broader risks associated with dynamic seismic wave propagation. Furthermore, conventional monitoring systems can be relatively expensive and require significant investment for installation, calibration, and maintenance.

In recent years, increasing attention has been directed toward the development and application of alternative technologies for seismic monitoring. One promising approach involves the use of audio records [4] (Skibic -Brzozowska, 2023) where advanced audio recording devices are capable of detecting frequencies below 20 Hz, which overlap with the frequency range of seismic waves generated by blasting activities, as well as natural seismic events that can extend below 1 Hz.

At the Faculty of Natural and technical sciences at University Goce Delcev in Stip, within the Department of surface mining and soil and rock mechanics, the geotechnology laboratory has developed a high-precision seismic data acquisition (DAQ) system for real time monitoring, processing and visualization [5] (Panov, Pekevski, & Popovski, 2023). The system is designed as a mobile, autonomous, and portable station, enabling seismic data collection at any location.

Through the analysis of seismic data obtained using audio recording systems, the research aims to improve existing monitoring practices, enhance safety, and contribute to the optimization of operational costs in mining processes [6] (Panov & Bikov, 2024).

Particular emphasis is placed on our prototype system, developed using the SBC Raspberry Pi 4, the high-precision ADS1263 AD HAT with an ultra-low-noise 32-bit analogue-to-digital (A/D) converter, and the EG-4.5-II geophone. The input range is ±2.5V, with the ability to amplify via a PGA, and sampling is done at 100 Hz [7] (Bikov, Panov, & Popovski, 2024).



Figure 2. Raspberry Pi 4, HAT ADS1263, and EG-4.5-II geophone [7] (Bikov, Panov, & Popovski, 2024)

Although the seismic data acquisition system has been successfully developed and implemented, the research is currently in the field testing and validation phase. The prototype has been deployed at several surface mines, where continuous seismic data acquisition is being carried out to evaluate its functionality, accuracy, and reliability under real mining conditions. Due to the ongoing stage of the research, a sufficient amount of experimental data has not yet been collected to perform a comprehensive quantitative analysis or to establish a direct comparison with conventional seismic monitoring methods. Nevertheless, the preliminary tests indicate that the system operates reliably and demonstrates significant potential for acquiring high-quality seismic records, providing a solid foundation for further research. The next phase of the study will focus on processing and analyzing the collected data, comparing the results with measurements obtained using standard seismological instruments, and evaluating the feasibility of the proposed system for practical application in monitoring blasting operations.

CONCLUSION

Based on the conducted analysis, it can be concluded that explosive blasting represents a significant source of induced seismicity that directly affects the stability of slopes in surface mines. The generated seismic waves cause dynamic stresses within the rock mass, which may lead to the formation of cracks, deformations, sliding, and rockfalls.

The intensity of these effects is directly dependent on the explosive charge, the distance from the blasting site, and the geomechanical characteristics of the rock mass. The application of empirical models, particularly the Sadowski relationship, enables reliable estimation of peak particle velocity (PPV) as a key parameter for risk assessment.

The analysis has shown that there are critical PPV values at which the rock mass transitions from elastic to plastic behavior, resulting in permanent damage and reduced slope stability. Therefore, defining these threshold values is essential for safe design and execution of blasting operations.

Furthermore, modern monitoring methods, especially the use of audio-based DAQ systems, represent an innovative and cost-effective solution for continuous seismic monitoring. These systems provide high precision, mobility, and real-time data analysis, significantly improving risk control and management.

By integrating conventional and modern monitoring approaches, a more efficient assessment of the dynamic effects of blasting can be achieved, contributing to improved safety, optimization of operational parameters, and sustainable management of surface mining operations.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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