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Impact of Blasting in the Open-Pit Mine on the Underground Mine

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Abstract **– The aim of this paper is to determine the impact of large-scale blasting at the ''Grivice'' open-pit mine on facilities and workers within the ''Underground Coal Mining'' mine, particularly with respect to the deepening of the open pit and the distance of the underground working faces. A detailed analysis of the blasting impact was carried out by measuring ground oscillation velocity and visually inspecting underground structures before and after blasting.**

Keywords **– open pit, underground mine, blasting, seismic impact, safety, environment.**

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1. Introduction

At the "RMU Banovići" surface mines, operations utilize a discontinuous mining complex that relies heavily on large-scale blasting. Currently, the closest proximity between these surface operations and underground mining activities occurs at the "Grivice" open-pit mine (OPM). Here, the spatial distance ranges between 400 and 500 meters, with a vertical height difference of approximately 260 meters. Given this close proximity and the intensive blasting required by the discontinuous complex, it is crucial to investigate the seismic impacts of these surface blasts on the underlying underground pit openings [1], [2].

To date, no established standards address the impact of surface-induced seismic waves on underground structures. Consequently, this study adopts a conservative maximum peak particle velocity threshold of v_{max}=0.4 (cm/s). A defining characteristic of this case is that large-scale blasting during the monitoring period occurred on higher benches dominated by clayey marls. Under these conditions, the seismic waves propagated through a highly heterogeneous series of lithological units before reaching the monitoring instruments. As the open-pit mine deepens, blasting environments will inevitably evolve, altering the established laws of seismic wave propagation. Therefore, continuous control measurements and subsequent optimization of blasting designs are planned to accommodate these changing geological conditions as depth increases [3], [9], [12].

The acoustic properties of the rock masses within the basin's exploitation area depend on several interconnected factors, including mineralogical composition, rock compactness, burial depth, and dynamic loading parameters. Variations in these acoustic parameters indicate significant fluctuations in rock mass characteristics across different spatial orientations and depths, underscoring the high complexity of the geotechnical environment for drilling and blasting operations.

Consequently, evaluating these acoustic parameters requires determining the propagation velocities of both longitudinal (P-wave) and transverse (S-wave) seismic waves as a function of the rock's elasto-dynamic properties [2], [4], [5].

Experimental studies demonstrate that the energy released during explosive detonation within a borehole generates intense dynamic loads on the borehole walls. This detonation process comprises three distinct phases: pressure accumulation against the borehole walls, shock wave reflection from the free surface, and subsequent gas expansion. Following these sequential phases, a seismic wave is generated. This wave consumes the majority of the explosion's total energy, propagating mechanical strain through the rock mass primarily behind and adjacent to the blasting block [1], [6], [11].

Explosive energy is transferred to the surrounding rock mass in two distinct forms: shock energy via the shock wave (comprising 15% of the total transferred energy) and gas energy via borehole pressure (comprising 85%). The total energy transferred through these mechanisms is consumed by various blasting phenomena. Certain phenomena are essential to the rock fragmentation process, and the energy consumed by them constitutes useful work; conversely, all other phenomena represent systematic energy losses [4], [5], [13].

As the shock wave propagates through the rock mass from the detonation source, it undergoes gradual attenuation until its energy is completely dissipated. In the immediate vicinity of the blast site, the shock wave induces compressive stresses that exceed the compressive strength of the rock mass, causing intense fragmentation. As the wave travels further and its energy dissipates, it induces tensile stresses that exceed the rock's tensile strength. Ultimately, at far-field distances, the wave weakens into a low-amplitude seismic wave that induces only elastic deformations within the rock mass. Nevertheless, despite this continuous attenuation with distance, blast-induced ground vibrations frequently remain perceptible at significant distances from the source [2], [3], [11], [13].

When a seismic wave propagates through a rock mass or soil, particles are displaced from their equilibrium positions and oscillate until the kinetic energy completely dissipates. This particle oscillation, within the geological medium, manifests as blast-induced ground vibrations. At near-field distances, these vibrations can induce structural damage in residential and industrial buildings by generating dynamic stresses that exceed the material's structural strength, mirroring the fracture mechanics observed in rock masses. Structures with lower structural stiffness relative to the surrounding rock mass are highly vulnerable to damage even at far-field distances if the blasting operations are poorly designed and executed.

Consequently, blast-induced ground vibrations and their adverse effects on structures and personnel have to be accurately predicted, monitored, and controlled to ensure both structural safety and the economic efficiency of the blasting process [5], [6], [10], [12].

Seismic waves are categorized into two primary classifications: body waves, which propagate through the internal rock mass, and surface waves, which travel along the terrain surface. Within body waves, two fundamental types are distinguished. The first type comprises longitudinal (compressional) waves, in which particle displacement occurs in a radial direction parallel to the direction of wave propagation. Due to the transmission of elastic deformations along the shortest path, longitudinal waves are the first to reach the monitoring station and are therefore designated as primary (P) waves. When a longitudinal wave impacts a free surface or a lithological boundary with contrasting physical and mechanical properties at a normal angle of incidence (90°), it reflects and generates the second type of body wave: the transverse wave. In a transverse wave, the excited medium particles oscillate within a plane perpendicular to the direction of wave propagation, inducing shear deformations. Consequently, transverse elastic waves are also referred to as shear or secondary (S) waves, as their lower propagation velocity causes them to arrive at the monitoring station after primary waves. A fundamental distinction between these wave types lies in their transmission media: longitudinal waves can propagate through solid, liquid, and gaseous phases, whereas transverse waves propagate exclusively through solid media [2], [5], [8].

2. Methodology

The research methodology comprises a comprehensive analysis of the existing literature and reference frameworks related to this geotechnical challenge. In-situ measurements of seismic parameters were conducted at selected representative monitoring stations. During large-scale blasting operations at the "Grivice" open-pit mine, instruments recorded the longitudinal, transverse, and vertical components of the particle velocity vectors, alongside the peak particle velocity (PPV), dominant frequencies, and accelerations. Concurrently, visual inspections of the underground structures were carried out immediately before and after each blasting event to document any structural modifications [8], [11], [13].

Seismic monitoring was performed utilizing advanced multi-channel data acquisition systems capable of registering all three orthogonal velocity components.

The field measurements were conducted using the following instrumentation:

- Instantel BlastMate III (integrated 8-channel monitoring system),
- Instantel MiniMate Plus (portable 4/8-channel seismograph).

To comprehensively define the operational framework, it is essential to establish the specific drilling and blasting parameters. In this study, the excavation phase utilized Gryphon-5C and Hausherr HBM 120 rotary blast-hole drilling rigs. The production blasting operations employed a combination of cartridge-plastic, powder, and emulsion explosives. The initiation sequence was configured using traditional safety fuses and No. 8 blasting caps, alongside a modern non-electric (NONEL) initiation system utilizing dedicated surface and in-hole NONEL detonators [9].

Factors that influence the characteristics of seismic waves caused by blasting are:

- Geomechanical properties of the rock mass and soil medium;
- Explosive mass per blasthole and delay detonator;
- Spatial distance between the blasting source and the monitoring station;
- Powder factor;
- Type of explosives;
- Optimal delay time;
- Initiation pattern;
- Blasthole diameter;
- Drilling deviation;
- Bench height;
- Burden, spacing, and sub-drilling length;
- Stemming column length;
- Blasthole inclination angle;
- Number of bore hole;
- Scatter of nominal delay time;
- Hole initiation timing and probability of overlap;
- Blasthole pattern/initiation timing and sequence.

Ground vibration monitoring is performed utilizing dedicated engineering seismographs. The "RMU Banovići" mine deploys two such instruments: an Instantel BlastMate III and an Instantel MiniMate Plus (Figure 1). These data acquisition systems continuously measure particle displacement, velocity, acceleration, and dominant frequency, while simultaneously recording blast-induced air overpressure (airblast).

Figure 1. Blastmate III and Minimate Plus seismographs

These systems comprise a triaxial geophone, an overpressure microphone, and a central data acquisition recorder. The geophone sensor housing contains three independent transducer units oriented orthogonally along mutually perpendicular axes. Functioning as an electromagnetic transducer, the geophone converts physical ground velocity into a corresponding analog electrical voltage. The electronic recording unit features an integrated microprocessor, internal storage memory, and an onboard thermal printer (BlastMate III), with native support for PC data transfer via proprietary analysis software. During field operations, geophones are anchored in situ near targeted structures at various designated monitoring stations. Within the generated summary report, the recorded frequency corresponds to the dominant frequency possessing the maximum kinetic energy during the blasting event. Throughout the monitoring window, longitudinal, transverse, and vertical wave components are completely registered. Figure 2 illustrates the characteristic output profile of Peak Particle Velocity (PPV) and air overpressure acquired by the Instantel MiniMate Plus seismograph.

Utilizing a sequence of analytical procedures and empirical formulations, the rock mass response can be delineated into distinct spatial zones: the immediate crushing zone, the transitional elasto-plastic deformation zone, and the far-field elastic deformation zone. This final elastic zone is the most geographically widespread and represents the primary focus within the field of blasting seismology [9], [10].

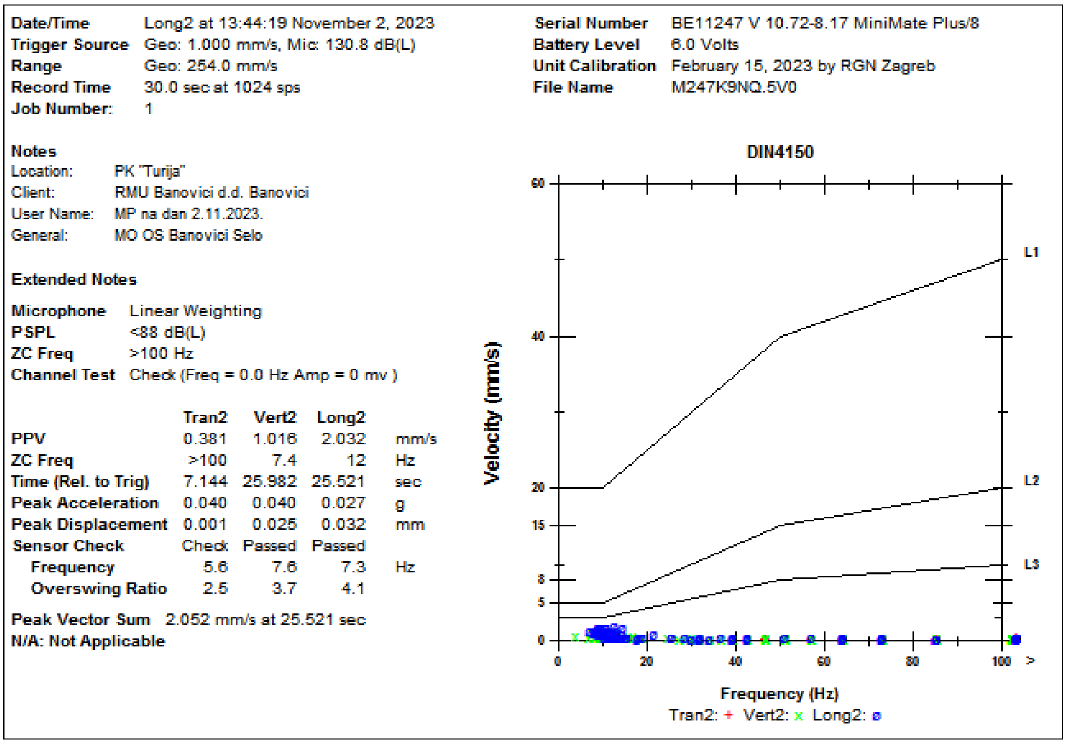

Figure 2. Representative data acquisition profile illustrating blast-induced ground vibration and air overpressure waveforms recorded via an Instantel BlastMate III seismograph

By monitoring particle oscillations within the far-field elastic deformation zone, researchers can systematically analyse several critical variables: the individual and combined blast design parameters that constitute the operational blasting framework, the influence of local geological and structural conditions, the effects of soil-structure interaction (SSI), and the structural response of building foundations to seismic wave propagation [1], [6], [13]. Underground seismic monitoring was conducted at three distinct positions within the mine workings: the OPZ_7 mechanized longwall face, the $OPZ_{6/2}$ mechanized longwall face, and the $OPZ_{1/3}$ semi-mechanized longwall face.

3. Results

After seismic measurements were performed and the collected data was analysed, the results were presented separately for each measurement point in the underground pit. In addition, the results of visual observation of the impact of blasting in the open pit on the excavations in the pit were also given.

3.1. Analysis of Measurement in Underground Openings OP_7 and $OPZ_{1/3}$

Field measurements along the mechanized longwall faces were conducted at the OPZ_7 location, which represents the closest underground mining front to the active operations at the "Grivice" open-pit mine (Figure 3).

Figure 3. Cross-section of a mechanized longwall face opening

Supplementary seismic monitoring was performed along the semi-mechanized longwall face within the $OPZ_{1/3}$ panel, situated in the western sector of the underground mine (Figure 4).

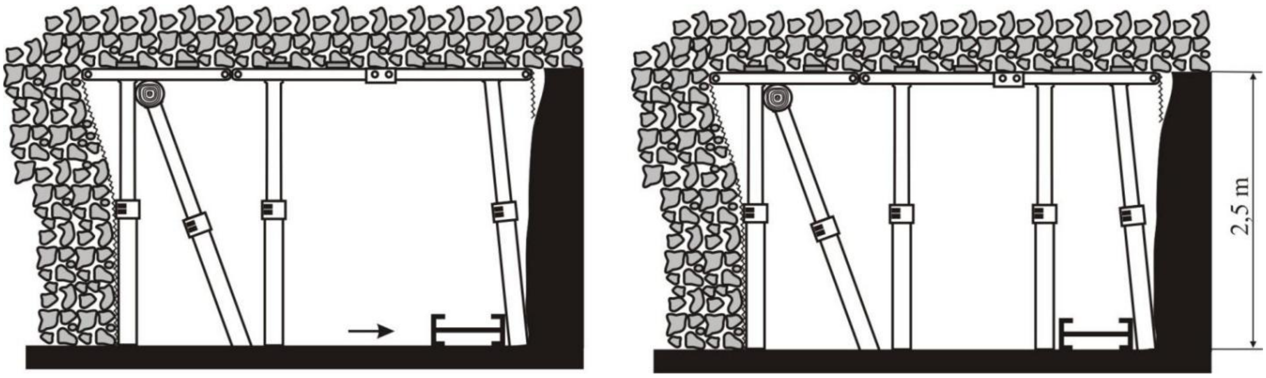

Figure 4. Cross-section of a semi-mechanized longwall face

The roof at this face is supported by TYPE OV-110 steel arches and friction props. To record seismic data, triaxial geophones were anchored directly into the floor of the underground mine opening adjacent to the armored face conveyor at monitoring stations 3 (MO_3) and 4 (MO_4).

Peak particle velocity (mm/s) can be calculated as (Equation (1)) [7]:

$$v = K \cdot \left(\frac{R}{\sqrt{W}}\right)^{-n} \quad (1)$$

K – blasting site coefficient;
R – spatial distance separating the blasting block from the monitoring station (m);
W – maximum charge weight per delay (kg);
n – attenuation coefficient.

Values of c, W and R, are measured in the field, but K and n are determined from linear least-squares regression analysis of log(v) vs. log($R/W^{1/2}$) [7].

By performing statistical regression analysis on the empirical field monitoring data, the specific rock mass parameters, namely the blasting site coefficient (K) and the seismic attenuation exponent (n)—were derived alongside the maximum allowable charge weight per delay (Table 1).

Table 1. Derived blasting site and seismic attenuation coefficients as a function of operational input parameters

	Minefield 63 for OPZ_7	Minefield 62 for $OPZ_{1/3}$
Max. instantaneous charge (kg)	65	65
Millisecond delay charge weight (kg)	255	300
Monitoring distance	MO_1 413 m	MO_3 360 m
Monitoring distance	MO_2 345 m	MO_4 985 m
PPV v_1 (cm/s)	0.26	0.533
PPV v_2 (cm/s)	0.383	0.0813
n	2.153	1.868
K	2090.45	911.507

Table 2 and Figure 5, as well as Table 3 and Figure 6, present the maximum allowable charge weights per delay for blasting blocks 63 and 62, respectively.

Table 2. Maximum allowable charge weight per delay (ms) for blasting block 63

m	1 (cm/s)	0,9 (cm/s)	0,8 (cm/s)	0,7 (cm/s)	0,6 (cm/s)	0,5 (cm/s)	0,4 (cm/s)	0,3 (cm/s)	0,2 (cm/s)
200	189.2	163.4	138.6	115.1	92.9	72	52.8	35.3	20.1
400	1513.6	1306.9	1109.1	920.8	742.8	576.2	422.2	282.8	160.7
600	5108.3	4410.8	3743.3	3107.8	2507.1	1944.7	1425	954.4	542.5
800	12108.6	10455.3	8872.9	7366.5	5942.7	4609.6	3377.8	2262.3	1285.9

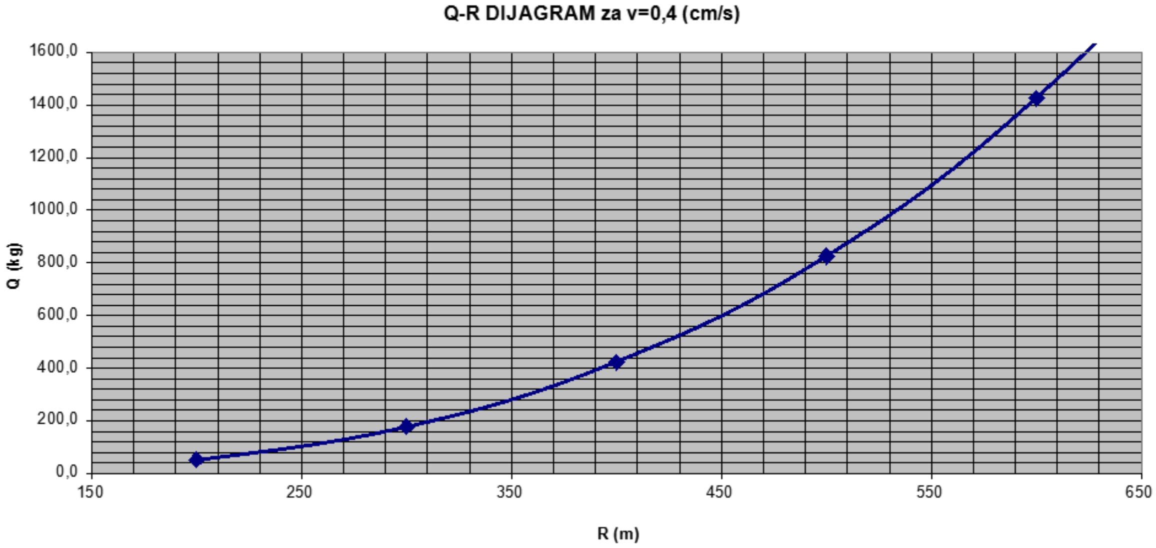

Figure 5.Q-R diagram for v=0.4 (cm/s) for blasting block 63

Table 3. Maximum allowable charge weight per delay (ms) for blasting block 62

m	1 (cm/s)	0,9 (cm/s)	0,8 (cm/s)	0,7 (cm/s)	0,6 (cm/s)	0,5 (cm/s)	0,4 (cm/s)	0,3 (cm/s)	0,2 (cm/s)
200	141.3	119.3	98.7	79.7	62.2	46.4	32.4	20.4	10.7
400	1130.4	954.4	790	637.5	497.7	371.4	259.5	163.5	85.3
600	3815.1	3221.2	2666.1	2151.6	1679.8	1253.4	875.9	551.9	287.8
800	9043.2	7635.6	6319.7	5100	3981.7	2971	2076.3	1308.1	682.1

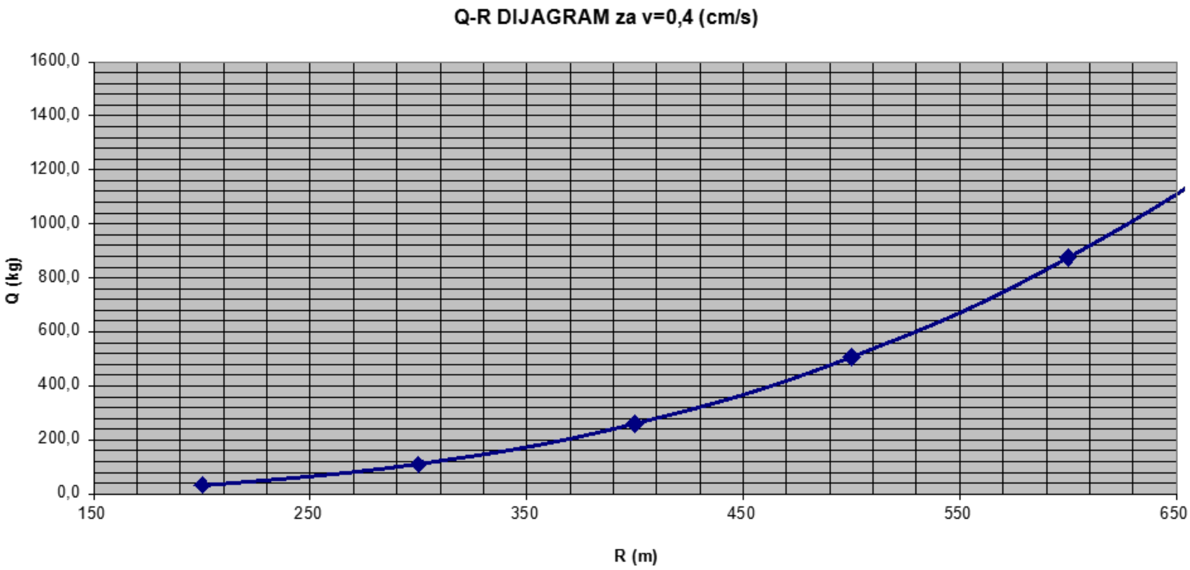

Figure 6. Q-R diagram for v=0.4 (cm/s) for blasting block 62

3.2. Analysis of Measurement in Underground Openings $OPZ_{6/2}$

Seismic monitoring was performed along the $OPZ_{6/2}$ mechanized longwall face to evaluate the impacts of surface blasting operations at the "Grivice" open-pit mine on the underlying infrastructure of the "Underground Coal Mining" facility.

The monitoring instruments were securely anchored into the floor of the underground mine opening. During the monitoring period, production blasting at the "Grivice" surface operations was executed on bench 268. A comprehensive summary of the seismic parameters recorded at this specific monitoring station is presented in Table 4.

Table 4. Empirical seismic monitoring results demonstrating the structural impacts of surface blasting operations at the "Grivice" open-pit mine on the underlying underground mining facilities

Underground measurement point	Opening elevation	Bench	Number of detonators	Charge weight (kg)	Measured seismic intensity levels (mm/s)	Seismic intensity level according to the IFZ scale
$OPZ_{6/2}$	107.2	268	11	172-292.5	3.86-8.12	III and IV
ŠČ $OPZ_{6/2}$	107.2	268	23	48-150	5.31-9.66	III and IV
First overpass $OPZ_{6/2}$	107.2	268	23	48-150	1.36-1.42	I

Subsequent control seismic monitoring was conducted on July 1, 2024, to evaluate production blasting executed under open-block configurations, with sensors anchored directly into the floor of the underground mine opening. The recorded seismic intensity was markedly lower than that of previous monitoring campaigns. During this specific blasting event, a total of 16 detonators were initiated within the blasting block, yielding a maximum charge weight per delay ranging from 96.0 to 237.5 kg of explosives. At monitoring station ŠČ $OPZ_{6/2}$, the instruments recorded a maximum peak vector sum particle velocity ranging between 4.137 and 5.187 mm/s.

An analysis of the monitoring results reveals that the majority of the registered seismic events fall within Intensity Level III of the International Force Zone (IFZ) scale, denoting macroseismic effects that are perceptible only by a small fraction of individuals or those actively expecting the vibration. Furthermore, the recorded dominant frequencies ranged between 20 and 64 Hz. Given this specific frequency band and the corresponding low vibration amplitudes, it can be concluded that these blast-induced ground motions will not induce adverse structural impacts on the monitored underground chambers.

3.3. Analysis of Observations in Underground Workings Before and After Blasting at the Open-Pit Mine

Visual inspections of the underground mine workings and associated facilities were systematically conducted immediately before and after each blasting event at the "Grivice" open-pit mine. No structural changes were observed; specifically, there was no evidence of fracturing within the roofs or ribs of the mine openings, nor was any detectable damage or deformation sustained by the underground support systems or facility infrastructure.

4. Discussion

Underground seismic monitoring campaigns were conducted across two distinct temporal windows: from April 20 to April 24, 2015, and from June 20 to July 1, 2024. These monitoring periods coincided with large-scale production blasting operations executed within the blasting blocks of the "Grivice" open-pit mine. Within these designated blocks, the explosive charge weight per delay ranged from 50 to 93 kg, while the total instantaneous charge weight for millisecond delay blasting sequences ranged between 255 and 715 kg. Beyond these charge masses, the overall seismic intensity was governed by additional influential variables, including the specific explosive formulations, the initiation methodology, the spatial orientation of the blasting blocks, and their geometric distance relative to the underground monitoring stations.

The designated monitoring stations were distributed across the underground workings, with locations MO_1 and MO_2 positioned along the mechanized longwall face, and MO_3 and MO_4 situated along the semi-mechanized longwall face. The spatial distance separating these monitoring stations from the active blasting blocks ranged between 360 and 985 meters. The recorded seismic parameters exhibited highly heterogeneous values. Specifically, the measured peak particle velocities ranged from 0.813 to 6.610 mm/s along the mechanized longwall face, and from 0.813 to 1.670 mm/s along the semi-mechanized longwall face, with both sectors characterized predominantly by low-frequency waveforms.

5. Conclusion

The primary objective of this study was to evaluate the structural and operational impacts of large-scale production blasting at the "Grivice" open-pit mine on the critical infrastructure, processing plants, and underground personnel within the "Underground Coal Mining" facility.

This assessment specifically analyzed these impacts as a function of increasing open-pit depth and the spatial distance to the underground longwall faces. The seismic effects of these blasting operations were definitively quantified through the empirical measurement of peak particle velocities, complemented by systematic visual inspections of the underground mine workings immediately before and after each blasting event. Based on the empirical field data and established operational experience, the spatial blast-impact zones regarding underground mine infrastructure were delineated as follows: Zone I extends up to a distance of 200 meters, Zone II spans between 200 and 500 meters, and Zone III encompasses all distances exceeding 500 meters. In accordance with these defined boundaries, targeted engineering mitigation and safety measures must be established for each zone. Furthermore, the analysis of the recorded seismic parameters enabled the calculation of the maximum allowable charge weight per delay, providing a predictive framework for the continuous optimization and planning of future production blasting operations. Implementing these protocols minimizes the adverse environmental and structural impacts of open-pit blasting, thereby ensuring the safe, uninterrupted continuity of extraction operations across both production facilities of "RMU Banovići."

This study demonstrates that seismic intensity fluctuates with the deepening of the "Grivice" open-pit mine, causing variable impacts on the "Underground Coal Mining" facility's infrastructure and personnel. Furthermore, evidence confirms these effects depend on the spatial distance between blasting blocks and monitoring stations, necessitating continuous, adaptive adjustments to blasting designs as the mine deepens. The analytical results reveal a wide spectrum of seismic wave propagation velocities, which consequently yielded highly variable calculated charge weights per delay. This variance is primarily attributed to the complex geotechnical conditions within the underground workings, as well as the profound influence of the blasting block's spatial orientation within the open-pit mine. Furthermore, parameters such as the initiation methodology, explosive formulation, blast-hole network geometry, and both the maximum instantaneous and millisecond delay charge weights played a significant role in altering wave propagation behavior.

By integrating the geomechanical properties of the rock mass with empirical seismic monitoring data under established drilling and blasting parameters, future blast designs for this site can be engineered with high precision. This predictive accuracy enables the systematic optimization of drilling and blasting configurations, effectively mitigating the adverse impacts of surface blasting on the underlying operations within the "Underground Coal Mining" facility.

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