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ASSESSMENT OF SEISMIC EFFECTS DURING MINING

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Abstract

The large application of the blasting technique in engineering arises from the fact that one blasting replaces months of work by machines and people. Wide application of the mining technique is due to the fact that during blasting the seismic impacts can be controlled and reduced to a minimum level. Today, blasting is often carried out in the immediate vicinity of various objects, buildings, factories, and even refineries, hydro facilities and nuclear power plants.

The assessment of blasting effects presented in this study is based on analytical calculations and widely used empirical relationships, with particular emphasis on the estimation of seismic impact through the Sadowski equation. The results for four minefields with explosive charges ranging from 100 kg to 3000 kg provide a comparative overview of how increasing explosive quantity influences fragmentation, airblast pressure, and ground vibration intensity.

Key words: *seismics, blasting, oscillations, effects, safety.*

INTRODUCTION

Today, there are various methods of destroying rock masses (mechanical, thermal, electro-physical, etc.), but the most widely used is still the mining technique. In mining blasting, rock masses are most often destroyed until they are suitable for exploitation. Depending on the volume mass that needs to be destroyed and then exploited, a blasting project is adopted.

In blasting, a single borehole (vertical, oblique or horizontal) is rarely used, and a larger number of boreholes arranged along a line or along several lines are often used. For mining, the use of multiple boreholes is particularly interesting, and such blasting is called mass blasting. In chamber blasting, explosives are placed in large quantities in separate galleries. This method of blasting is most often used in mining during day excavations. The depth (in mining up to 70 m) and diameter (38 - 300 mm) of the borehole varies from task to task. The geometry and number of holes depend on the mass to be destroyed. The holes are filled continuously or intermittently with various types of explosives.

In a minefield, there are boreholes with different purposes: destructive (R) and shock-absorbing (A). Destructive holes are used to perform useful work, while shock-absorbing holes are used to mitigate seismic shocks behind the minefield and better form the separation surface. Shock-absorbing holes are filled with a smaller amount of explosive than destructive holes, and sometimes remain empty [1, 2].

When a larger number of boreholes are mined, they are activated simultaneously (instantaneously) or with a time shift. The activation time interval between two boreholes or a series of holes varies from 10 ms to 0.1 s (Fig. 1).

The hole is detonated from the surface to the bottom or vice versa. The direction and sequence of activation of the boreholes is set on the minefield in the direction where the main seismic shock is desired to be directed.

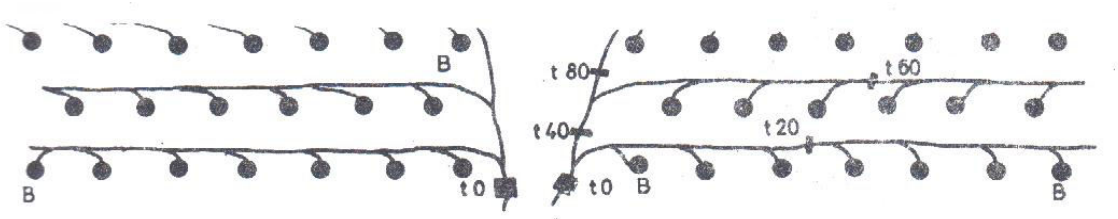


Figure 1. Instantaneous (a) or millisecond (b) activation of a large number of boreholes (B – hole, t0 .. t80 – retardation between groups of boreholes in milliseconds)

The boreholes are filled with different types of explosives (with different blasting power, detonation velocity, energy, volume weight, etc.), depending on the desired crushing effect. The amount of explosive or the filling per m^3 depends on the hardness, volume weight, seismic impedance of the rock mass being destroyed on the one hand and the characteristics of the explosive on the other. The blasting parameters (number, depth, diameter, geometry, quantity, type and system of filling the boreholes, method of activation - instantaneous or millisecond, number of boreholes per activation interval, etc.) should be selected so that most of the energy is used for useful work, and as little as possible for seismic shocks. Since the seismicity of the blasting depends on all the parameters, but also on the distance of the observation point from the minefield, determining the way in which the mining work is carried out is a rather complex task.

MATERIAL AND METHODS

When blasting into rock masses, the released energy causes three main physical effects that can be dangerous to people, equipment and structures near the minefield [3-8]:

1. Fragmentation – Scattering of rock fragments under the action of the detonation force
2. Shock (detonation) wave - rapid propagation of a pressure wave through the air
3. Seismic impact - propagation of elastic waves through the rock environment.

In engineering practice, the observation or protection distance is defined based on the spatial (real) distance, not just the horizontal one. When the minefield and the observation point are at different elevations, the following equation applies:

$$\sqrt{(r_a^2 + \Delta H^2)} = \sqrt{(250^2 + 40^2)} = \sqrt{64100} \approx 253\,m$$

where r_a is the horizontal distance between the minefield and the observation point and ΔH is the height distance.

Fragmentation

The empirical dependence for estimating the maximum range of fragments during detonation:

$$L_{min} = 10 \times Q^{1/3}$$
$$L_{max} = 15 \times Q^{1/3}$$

where Q is the amount of explosive in kg, and $Q^{1/3}$ is the scaled charge factor ($kg^{1/3}$).

The zone of elastic deformations (seismic zone) begins at:

$$r_{el} = 0.12 \times Q^{1/3}\ [m]$$

Detonation wave energy

The total energy released during detonation is:

$$E = Q \times e_{spec}$$

where e_{spec} = 4.2 MJ/kg is the specific energy of a standard industrial explosive.

The pressure of the shock wave at a certain distance is estimated by a scaled dependence:

$$P \approx C \times (Q^{1/3} / R)$$

where C is an empirical constant dependent on the environment and type of blasting.

Seismic influence - Sadowski equation (1966)

The most used equation for ground oscillation velocity in engineering practice is:

$$V = K \times (Q^{1/3} / R)^n \ [cm/s]$$

where:

V - ground oscillation velocity [cm/s]
K - coefficient depending on geological conditions (K = 200 for medium-hard rocks)
Q - mass of the explosive filling [kg]
R - spatial distance to the observation point [m]
n - exponent dependent on geological conditions (n = 1.6)

The Sadowski empirical equation is widely used in engineering practice for estimating peak particle velocity (PPV) due to its simplicity and practical applicability. It is important to note that this equation is site-dependent and requires calibration based on local geological and geomechanical conditions. The coefficients K and n vary significantly depending on rock mass properties, discontinuities, and blasting design. The applicability of the equation is generally limited to conditions like those under which it was derived, typically medium-hard rock environments and controlled blasting operations.

Therefore, the results obtained in this study should be considered as preliminary engineering estimates, and for higher accuracy, site-specific calibration using field measurements is recommended.

The equation is derived based on the principle of dynamic similarity - when the radius of the explosive filling and the distance increase proportionally, the oscillation velocity remains constant.

RESULTS AND DISCUSSION

Examples of an assessment of the effects of blasting

For the purposes of this analysis, four different minefields with different amounts of explosives are considered. The blasting is carried out with a NONEL initiation system with a millisecond delay.

The minefield is located at an elevation of 640 m, while the observation point is located at an elevation of 600 m, at a horizontal distance of 250 m. The real spatial distance is: R = 253 m

The analysis includes the following effects:

1. Scattering of fragments of mined material
2. Detonation wave force
3. Seismic impact (oscillation speed)

Due to the lack of available field measurements from active blasting operations, the analysis in this study is based on analytical and empirical models. Although these approaches are widely accepted in preliminary design, the absence of real-time seismic monitoring represents a limitation. Future research should include in-situ measurements using seismographs to validate and calibrate the predicted oscillation velocities.

Minefield no. 1 (100 kg explosive)

1. Scattering of fragments

The range of fragments upon detonation is estimated by an empirical dependence based on the scaled cube root of the mass of the explosive:

$$Q^{1/3} = 100^{1/3} = 4.642\ kg^{1/3}$$
$$L_{min} = 10 \times Q^{1/3} = 10 \times 4.642 = 46.42\ m$$
$$L_{max} = 15 \times Q^{1/3} = 15 \times 4.642 = 69.63\ m$$

Estimated fragment range: 46.42 m to 69.63 m

The observation point is located at a spatial distance R = 253 m. So, the observation point (253 m) is OUTSIDE THE BLASTING ZONE (69.6 m) - SAFE

Radius of the zone of elastic deformations:

$$r = 0.12 \times Q^{1/3} = 0.12 \times 4.642 = 0.56\ m$$

The observation point (253 m) is outside this zone.

2. Detonation wave force

The total energy released during detonation:

$$E = Q \times e_{spec} = 100 \times 4.2\,MJ/kg = 420\,MJ$$

The transmission of the shock wave through the air is estimated by an empirical scaled dependence:

$$P \approx C \times (Q^{1/3}/R) \rightarrow P \approx Q^{1/3}/R = 4.642 / 253 = 0.01835$$

Estimated impact pressure at a distance 253 m: 1.5 - 2.8 kPa

✓ Pressure < 5 kPa → Safe for people and standard structures

3. Seismic impact - Oscillation velocity (Sadowski)

According to Sadowski's (1966) equation for ground oscillation velocity:

$$V = K \times \left(Q^{1/3}/R\right)^{n}\,[cm/s] =$$

$$= 200 \times (4.642/\,253)^{1.6} = 200 \times (0.01835)^{1.6} = 0.333\,[cm/s]$$

where:

K = 200 (constant for medium-hard rocks)

n = 1.6 (exponent, field-determined)

Q = 100 kg (quantity of explosives)

R = 253 m (spatial distance)

Oscillation velocity: **V = 0.333 cm/s** → Intensity: **II - III**

✓ **Barely registered — not felt by humans (below the threshold of perception 0.5 cm/s)**

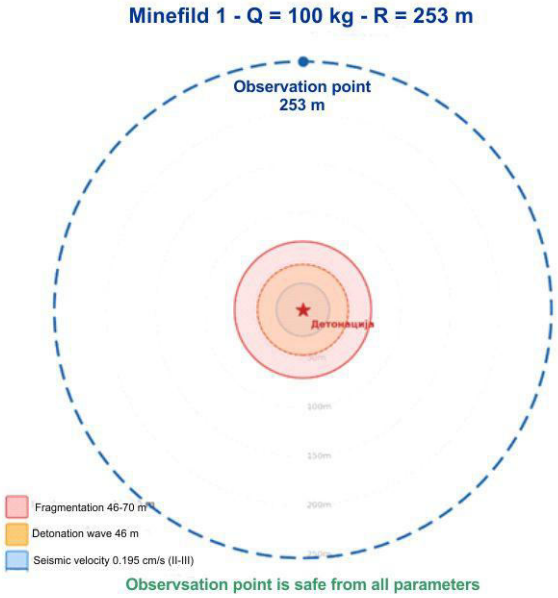


Figure 1. Illustration of effects of blasting when using 100 kg explosive

Minefield no. 2 - Q = 250 kg

1. Scattering of fragments

$$Q^{1/3} = 250^{1/3} = 6.300\,kg^{1/3}$$

$$L_{min} = 10 \times Q^{1/3} = 10 \times 6.300 = 63.0\,m$$

$$L_{max} = 15 \times Q^{1/3} = 15 \times 6.300 = 94.5\,m$$

Estimated fragment range: 63.0 m to 94.5 m

The observation point is located at a spatial distance R = 253 m. So, the observation point (253 m) is OUTSIDE THE BLASTING ZONE (94.5 m) - SAFE

Radius of the zone of elastic deformations:

$$r = 0.12 \times Q^{1/3} = 0.12 \times 6.300 = 0.76\,m$$

The observation point (253 m) is outside this zone.

2. Detonation wave force

The total energy released during detonation:

$$E = Q \times e_{spec} = 250 \times 4.2\,MJ/kg = 1050\,MJ$$

The transmission of the shock wave through the air is estimated by an empirical scaled dependence:

$$P \approx C \times (Q^{1/3}/R) \rightarrow P \approx Q^{1/3}/R = 6.300/253 = 0.02490$$

Estimated impact pressure at a distance 253 m: 2.0 – 3.7 kPa

✓ Pressure < 5 kPa → Safe for people and standard structures

3. Seismic impact - Oscillation velocity (Sadowski)

According to Sadowski's (1966) equation for ground oscillation velocity:

$$V = K \times \left(Q^{1/3}/R\right)^{n}\,[cm/s] =$$

$$= 200 \times (6.300/253)^{1.6} = 200 \times (0.02490)^{1.6} = 0.543\,[cm/s]$$

Oscillation velocity: **V = 0.543 cm/s** → Intensity: **III - IV**

✓ **It feels weak - people register it, no damage**

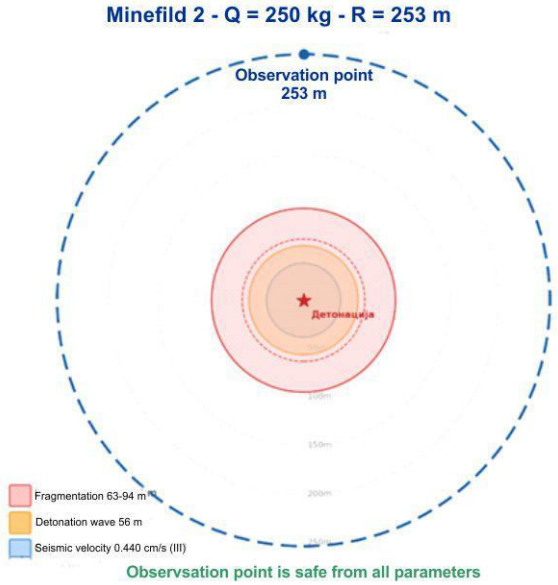


Figure 2. Illustration of effects of blasting when using 250 kg explosive

Minefield no. 3 - Q = 1000 kg

1. Scattering of fragments

$$Q^{1/3} = 1000^{1/3} = 10.000\,kg^{1/3}$$

$$L_{min} = 10 \times Q^{1/3} = 10 \times 10.000 = 100.0\,m$$

$$L_{max} = 15 \times Q^{1/3} = 15 \times 10.000 = 150.0\,m$$

Estimated fragment range: 100.0 m to 150 m

The observation point is located at a spatial distance R = 253 m. So, the observation point (253 m) is OUTSIDE THE BLASTING ZONE (150 m) - SAFE

Radius of the zone of elastic deformations:

$$r = 0.12 \times Q^{1/3} = 0.12 \times 10.000 = 1.20\,m$$

The observation point (253 m) is outside this zone.

2. Detonation wave force

The total energy released during detonation:

$$E = Q \times e_{spec} = 1000 \times 4.2\,MJ/kg = 4200\,MJ$$

The transmission of the shock wave through the air is estimated by an empirical scaled dependence:

$$P \approx C \times (Q^{1/3}/R) \rightarrow P \approx Q^{1/3}/R = 10.000/253 = 0.03953$$

Estimated impact pressure at a distance 253 m: 3.2 - 5.9 kPa

✓ Pressure 5–15 kPa → Possible slight damage to glass and fragile elements.

3. Seismic impact - Oscillation velocity (Sadowski)

According to Sadowski's (1966) equation for ground oscillation velocity:

$$V = K \times \left(Q^{1/3}/R\right)^{n} [cm/s] =$$

$$= 200 \times (10.000/253)^{1.6} = 200 \times (0.03953)^{1.6} = 1.138\,[cm/s]$$

Oscillation velocity: **V = 1.138 cm/s** → Intensity: **IV - V**

◉ **Moderate — clearly felt, possible microcracks in old buildings**

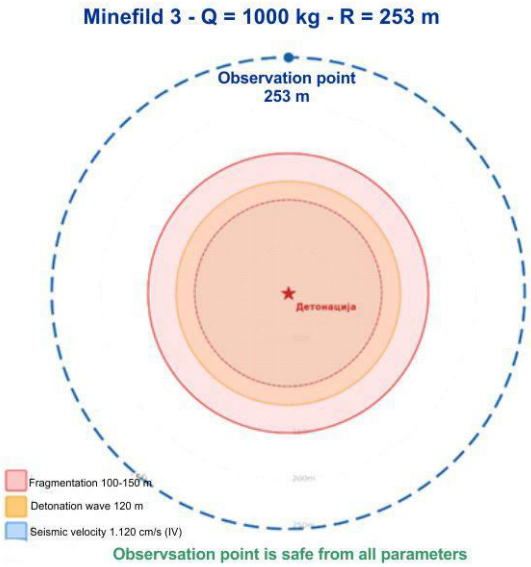


Figure 3. Illustration of effects of blasting when using 1000 kg explosive

Minefield no. 4 - Q = 3000 kg

1. Scattering of fragments

$$Q^{1/3} = 3000^{1/3} = 14.422\,kg^{1/3}$$

$$L_{min} = 10 \times Q^{1/3} = 10 \times 14.422 = 144.2\,m$$

$$L_{max} = 15 \times Q^{1/3} = 15 \times 14.422 = 216.3\,m$$

Estimated fragment range: 144.2 m to 216.3 m

The observation point is located at a spatial distance R = 253 m. So, the observation point (253 m) is OUTSIDE THE BLASTING ZONE (216.3 m) - SAFE

Radius of the zone of elastic deformations:

$$r = 0.12 \times Q^{1/3} = 0.12 \times 14.422 = 1.73\,m$$

The observation point (253 m) is outside this zone.

2. Detonation wave force

The total energy released during detonation:

$$E = Q \times e_{spec} = 3000 \times 4.2\,MJ/kg = 12600\,MJ$$

The transmission of the shock wave through the air is estimated by an empirical scaled dependence:

$$P \approx C \times (Q^{1/3}/R) \rightarrow P \approx Q^{1/3}/R = 14.422/253 = 0.05701$$

Estimated impact pressure at a distance 253 m: 4.6 – 8.6 kPa

✓ Pressure 5–15 kPa → Possible slight damage to glass and fragile elements.

3. Seismic impact - Oscillation velocity (Sadowski)

According to Sadowski's (1966) equation for ground oscillation velocity:

$$V = K \times \left(Q^{1/3}/R\right)^{n} [cm/s] =$$

$$= 200 \times (14.422/253)^{1.6} = 200 \times (0.05701)^{1.6} = 2.044\ [cm/s]$$

Oscillation velocity: **V = 2.044 cm/s** → Intensity: **V - VI**

✓ **Moderate — clearly felt, possible microcracks in old buildings**

⚠ **Strong — possible cracks, structural analysis of the construction is required**

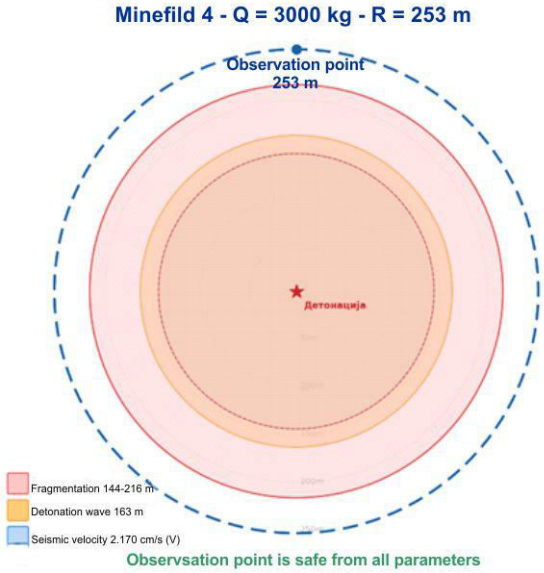


Figure 4. Illustration of effects of blasting when using 3000 kg explosive

Table 1. Oscillation velocity criteria (V) according to international standards and practices in blasting

V (cm/s)	Intensity	Effect description
< 0.5	I - II	Not felt - only instrumentally measurable
0.5 – 1.0	II - III	Weakly felt - no damage to structures
1.0 – 2.5	III - IV	Clearly felt - possible microcracks in old buildings
2.5 – 5.0	IV - V	Moderate - possible cracks, damage to fragile structures
> 5.0	V+	Strong - significant damage, protective measures required

Table 2. Summary results from all analysis

Mine-field	Q (kg)	Scattering fragments (m)	Energy (MJ)	Pressure (kPa)	V (cm/s)	Intensity	Safety
No. 1	100	46.4 - 69.6	420	1.5 - 2.8	0.333	II - III	Safe zone
No. 2	250	63.0 - 94.5	1050	2.0 - 3.7	0.543	III - IV	Safe zone
No. 3	1000	100.0 - 150.0	4200	3.2 - 5.9	1.138	IV - V	Safe zone
No. 4	3000	144.2 - 216.3	12600	4.6 - 8.6	2.044	V - VI	Safe zone

CONCLUSION

There are various methods of rock mass destruction, but the most widely used technique is blasting. Blasting remains the most widely applied method for rock mass excavation in mining and civil engineering due to its efficiency and adaptability. However, its application is inherently associated with potentially harmful effects, including fragmentation, airblast pressure, and seismic ground vibrations, which must be carefully assessed to ensure operational safety.

During blasting, shock, elastic-plastic and elastic waves occur in rock masses.

For engineering practice, especially for seismicity during blasting, the zone of elastic deformations is of interest, i.e., the zone through which seismic waves propagate.

Based on the analysis of the four minefields with explosive quantities of 100 kg, 250 kg, 1000 kg and 3000 kg, at an elevation of 640 m, in relation to the observation point at an elevation of 600 m and an air distance of 250 m (R = 253 m), the following conclusions are drawn:

- The observation point is safe in all four minefields. The maximum range of fragments scattering, in the 3000 kg minefield (216 m), does not reach the distance of 253 m. However, the difference is relatively small and when blasting with 3000 kg, the use of protective nets is recommended.

- The impact pressure increases with the cube root of the explosive mass ($Q^{1/3}$). In small fields (100 - 250 kg) the pressure is within 1 - 4 kPa - safe for people. In the 3000 kg field, the pressure reaches 6 - 9 kPa - permissible in mining conditions, but with eye and ear protection.

- The oscillation speed increases significantly with the amount of explosive. At 100 kg and 250 kg it is below the threshold of perception (V < 0.55 cm/s). At 1000 kg, intensity IV (V = 1.14 cm/s) is reached - clearly perceptible. At 3000 kg the intensity is V = 2.04 cm/s - possible microcracks in old structures. The use of a NONEL system with a millisecond delay can reduce the effective seismic values by 30-50%.

General conclusion is that the observation point at distance of 253 m is within permissible limits for all four minefields, provided that appropriate protective measures are applied for larger quantities of explosives (1000 kg and 3000 kg).

It is important to emphasize that these results are based on empirical models that rely on generalized assumptions. The Sadowski equation, although widely used in engineering practice, is site-dependent and requires calibration through field measurements for accurate application. The use of standard coefficients in this study represents a limitation, as local geological conditions, rock mass heterogeneity, and blasting design parameters can significantly influence seismic wave propagation.

An additional limitation of this study is the absence of real-time field data for validation. Without direct comparison to measured vibration values, the presented results should be considered as preliminary engineering estimates. For practical applications, especially in sensitive environments, it is essential to perform in-situ monitoring using appropriate instrumentation and to adjust empirical parameters accordingly.

Despite these limitations, the results obtained are consistent with commonly reported values in literature and provide a reasonable basis for preliminary assessment of blasting effects. The analysis also highlights the importance of controlled blasting techniques, such as the use of NONEL initiation systems with millisecond delays, which can significantly reduce seismic impact by lowering the effective charge per delay interval.

Future research should focus on integrating empirical models with field measurements and advanced predictive approaches, including numerical simulations and data-driven methods, to improve the accuracy and reliability of seismic impact assessments. Such approaches would enable more precise evaluation of site-specific conditions and contribute to safer and more efficient blasting design.

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