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Review paper

CRITERIA FOR EVALUATION THE SEISMIC EFFECT OF BLASTING

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Abstract:

The explosion that caused by blasting is accompanied by the release of a large amount of energy. That energy can be used for rock mass destruction. At the same time, one part of that energy is utilized for rock destruction while the second one gets lost in the rock mass in the form of seismic wave. Regarding that, blasting effects can be divided into two categories such as: useful work and useless work. Useful work is manifested in form of crushing and milling of the rock material in the limited zone around explosive matter and is defined as brisant effect of explosion. Useless work is a phenomenon known as seismic effect of explosion. Useless work is associated with the elastic displacement i.e., the oscillation of the rock mass particles in a very large space around the place of explosion and is felt as a shock. Oscillation velocity of the induced rock mass is most often taken as the parameter for the evaluation the seismic effect of blasting. It is considering that the oscillation velocity best relates and describes the danger of shocks and damages which can be caused, so the appropriate standards for the shock protection are based on the data related to the oscillation velocity. In many countries, regulations that control the shock level caused by blasting activities have been adopted. For our country, these regulations have not yet been adopted, so we used the regulations of other countries to solve these problems. In this paper, criterion of the Institute of Physics of the Earth, Russian Academy of Sciences, criterion according to the Russian standards for mining objects, criterion according to the German standards DIN and criterion according to the USA standards are presented.

Keywords: blasting, seismic effect, oscillation velocity, criterion for the damage evaluation

1 INTRODUCTION

Explosion, that caused by detonation of explosive materials, is accompanied by the release of a large amount of energy. That energy manifests a huge strength in short time intervals and can be used for rock mass destruction. One part of that energy is used for

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rock destruction and the other part gets lost in the rock mass in the form of seismic wave. Seismic waves caused by blasting act in the same way and have the same character as seismic waves caused by an earthquake. What makes seismic waves caused by an earthquake and by explosive different from each other is: the energy they transmit, range of influence, time of duration, frequency dynamic characteristic of seismic waves (Peng et al., 2019).

What additionally differentiates an uncontrolled explosion in the Earth's crust – related to earthquakes, from a controlled explosion – related to detonation of explosive materials, is the knowledge of the energy that is released on that occasion. In the case of an earthquake, we get to the amount of the energy that is released only after it has happened and after determining the consequences of its effect. In the case of detonation of explosive material, we know in advance the amount of energy that is released, and we can define the part that will be the carrier of seismic shock. Thanks to this possibility, it is possible to estimate the range and intensity of the seismic wave for controlled explosions (Dao et al., 2021).

2 EXPLOSION EFFECT ON WORKING ENVIRONMENT

During the explosion, one part of the energy is used for rock mass destruction and the other part of the energy gets lost in the rock mass in the form of seismic wave. Depending on distance from the center of explosion, different changes occur in the rock mass. In a homogeneous and isotropic environment, three zones can be distinguished:

-crushing zone,
-destruction zone and
-shock zone.

In the crushing zone, the shock wave exerts pressure on the surrounding rocks at a velocity greater than the sound velocity, while in the zone around the explosion space, at a distance (3–7)r, where r is the radius of explosive charge, the rock material gets crushed and compressed into the rock mass. The resulting pressure multiple overcomes the compressive strength of the rock, from 40 to 400 times. In this zone, rock crushing is the most intensive and the largest amount of the available energy is consumed.

Destruction zone occurs at a distance greater than (3–7)r. In this zone, the shock wave is significantly weakened and moves at the sound velocity. It causes stresses in the surrounding rock materials which resulting in the creation of cracks of different directions and orientations. Radial and concentric cracks or their combinations are formed.

Shock zone occurs when the shock wave is weakened so much that it is able to only move particles in the domain of elastic deformations. In this zone, there is no destruction but a rock mass particles displacement which is felt as shock. Elastic waves that propagate in this zone have the nature of seismic waves.

From the point of view of exploitation, when the rock is destructed by explosive, the crushing zone and destruction zone are important. The third zone, in which only particles move in the domain of elastic deformations, is also known as seismic zone. This zone does not affect the destructions effects but can be harmful to objects in the environment, both on the surface and underground.

A representation of the deformation zones during the explosion is given in Figure 1. Deformation zones because of explosion in homogeneous and solid rock mass are shown in Figure 1a. In such environments, three deformation zones are clearly observed: crushing zone, destruction zone and shock zone. During the blasting activities in soft, plastic, and unbound rock material, the following zones should be distinguished: extrusion zone, plastic deformation zone and elastic deformation zone, which are shown in Figure 1b. In such environments, the extent of destruction under the influence of stresses caused by shock wave is insignificant due to their plastic properties.

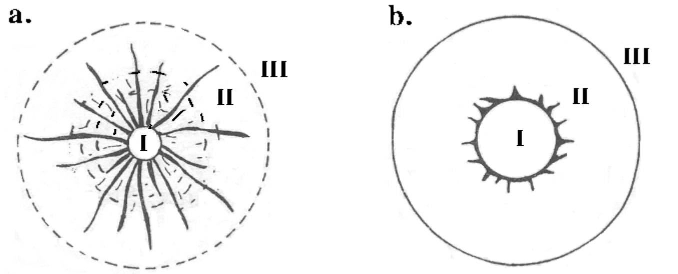

Figure 1 A representation of deformation zones during explosion:
a. in homogeneous and solid rock material, I – crushing zone, II – destruction zone, III – shock zone
b. in plastic and unbound rock material, I – extrusion zone, plastic deformation zone, III – elastic deformation zone

Blasting effects can be divided into two categories:

-useful work and

-useless work.

Useful work is manifested in the form of crushing and milling of the rock material in the limited zone around explosive matter and is defined as brisant effect of explosion. Work related to the crushed rock material displacement by products of explosion i.e., by gases is defined as fugitive effect of explosion.

Useless work is a phenomenon known as seismic effect of explosion. Work is related to elastic displacement i.e., the oscillation of the rock mass particles in a very large space around the place of explosion.

3 PARAMETERS OF THE ROCK MASS OSCILLATION

When a seismic wave hits a point in the terrain, it pushes the soil particles at that point out of their equilibrium position and they oscillate around their equilibrium position for a certain time until they completely settle down. Particles oscillation of the rock material (terrain or soil) is what manifests itself and is felt as a shock, i.e., soil vibration.

The waves move at high velocities through the rock mass (300 –7000 m/s), at long distances, inducing the particles oscillation at the points they encounter. The material particles of the mass do not move anywhere, but only oscillate around their equilibrium position at much lower velocities, of the order of mm/s, until the oscillations are dampened, i.e., until the rock mass settles.

Shock intensity caused by blasting activities can be established by measuring one of the three basic parameters that characterize oscillation of induced soil, those are:

- rock mass particles displacement x is the distance where the particle moves away from its equilibrium position during the oscillation. It is expressed in mm or in parts of mm.
- oscillation velocity of the rock mass particles v is the displacement velocity of the particles during the oscillation. It is expressed in mm/s or cm/s.
- acceleration of the induced environment a show the degree of change of the oscillation velocity i.e., particles displacement

The magnitudes of these three parameters indicate the force intensity with which they were caused, and therefore the degree of danger caused by the shock. These parameters represent the basic dynamic parameters of the shock. Oscillation velocity of the induced rock mass is most often taken as the parameter for the evaluation of the seismic effect of blasting. It is considered that the oscillation velocity best relates and describes the danger of shocks and damages which can be caused, so the appropriate standards for the shock protection are based on the data related to the oscillation velocity.

4 ROCK MASS OSCILLATION VELOCITY EQUATION

Rock mass oscillation velocity equation defines velocity alteration of rock mass oscillation depending on distance, explosive amount, properties of rock material and blasting method. The equation, defined in this way, offers the possibility to determine the seismic effect of blasting towards a structure, whereby the connection between the rock mass oscillation velocity and consequences that can affect facilities, is used.

The equation of M.A Sadovskii (Medvedev, 1964) is given in the form

$$v = K \cdot R^{-n} = K \cdot \left(\frac{r}{\sqrt[3]{Q}}\right)^{-n} \quad (1)$$

where there are:

v – rock mass oscillation velocity $[cm/s]$,

K – coefficient conditioned by rock mass characteristics and blasting conditions,
n – exponent conditioned by characteristics of rock mass and blasting conditions,

r – distance from the blasting site to the monitoring point $[m]$,

Q – total amount of explosive $[kg]$,

R – the reduced distance, given in the form $R = \frac{r}{\sqrt[3]{Q}}$.

The Sadovskii equation is determined based on test blasting for the concrete working environment.

In the Equation (1) two parameters appear, K and n, which need to be determined for a specific work environment and specific blasting conditions. The Least Square Method is mainly used to obtain the parameters K and n which represents a common model (Simeunović, 1985).

5 DAMAGE EVALUATION OF THE BLASTING

Explosive materials in mining, geology, construction, and other industries, with their effect, disrupt the natural environment in the form of crushing, scattering pieces of rock, air strikes, occurrence of seismic effects, etc.

The basic requirement for the use of explosive devices is that the mentioned effects do not adversely affect people who have direct or indirect contact with the environment within the minefield, as well as that they do not damage residential or industrial buildings that can be found in the field of their effect.

In most countries, regulations have been adopted that regulate the level of shock caused by blasting, which can load buildings, depending on their importance, condition, and dynamic resistance. The regulations are in accordance with the seismic and geological conditions, which are characteristic of a particular country. Such regulations have not yet been adopted for our country, so in solving this problem we use the regulations and norms of other countries, most often Russian, German, and American.

Before blasting activity, it is necessary to perform the categorization of the condition of the objects located in the immediate vicinity of the blasting site, according to their resistance to shocks and oscillations. According to this criterion, all objects are classified into three basic categories, and they refer to buildings that were not built according to regulations.

Type A. This type includes buildings that were built from raw stone, rural buildings from unbaked bricks, buildings with walls plastered with mud, which practically means that they are the least resistant to shocks and vibrations.

Type B. This type includes buildings made of baked bricks, buildings built of blocks and prefabricated buildings (from prefabricated materials), buildings made of natural hewn stone, as well as buildings with partially wooden construction.

Type C. This type of construction includes buildings built with reinforced concrete construction and well-built wooden houses. This type of building is also the most resistant to shocks and vibrations.

In order to define the condition of the object, it is necessary to determine the degree of object damage. Damages on objects are classified into five degrees.

I degree – light damages. Small cracks in the plaster. Lime falling off the ceilings, small pieces of plaster falling off.

II degree – moderate damages. Small pieces of plaster falling from the ceiling and walls, small cracks in the walls, tiles falling from the roof, parts of the chimney falling from the roof.

III degree – hard damages. Deep cracks in the walls, delamination and falling of the ceiling, chimney falling from the roof.

IV degree – destruction. Open cracks in the walls, demolition of parts of the building, breaking of connections between individual parts of buildings, demolition of internal walls of buildings.

V degree – absolutely destruction. Complete separation of the structure and demolition of the building.

5.1 Criteria for shock evaluation of the blasting

Shock intensity caused by blasting is sometimes evaluated using a scale applied in seismology, most often the Mercalli – Cancani – Sieberg (MCS) scale. Although there is a similarity between shocks caused by blasting and earthquakes, the differences are significant especially during the duration of the earthquake and period of oscillation (Anas et al., 2022). Those differences exclude the possibility of applying the MCS scale for shock intensity evaluation caused by blasting. Today in the world there are many specialized scales for shock intensity evaluation caused by blasting (Savić, 2000).

5.1.1 Criterion of the Institute of Physics of the Earth, Russian Academy of Sciences[3]

The permissible shock intensity for objects of different resistivity is related to rock mass oscillation velocity. The degree of seismic intensity is given in the form of twelve seismic degrees. Russian scale for shock evaluation caused by blasting is established in the Institute of Physics of the Earth, Russian Academy of Sciences. The evaluation of the seismic intensity of shock is given in Table 1.

Table 1 The evaluation of the seismic intensity of shock according to criterion IFZ Russia

Oscillation Velocity $v[cm/s]$	Level of seismic intensity I	Description of actions
To 0,2	I	Action is revealed only by instruments
0,2–0,4	II	Action is felt only in some cases when there is a complete silence
0,4–0,8	III	Action is felt by very few people or only those who are expecting it
0,8–1,5	IV	Action is felt by many people, the clink of the windowpane is heard
1,5–3,0	V	Plaster fall, damage on buildings in poor condition
3,0–6,0	VI	Air cracks in plaster, damage, damage to buildings that already have developed deformations
6,0–12,0	VII	Damage on the buildings in good condition, cracks in plaster, parts of the plaster fall down, air cracks in walls, cracks in tile stoves, chimney wrecking
12,0–24,0	VIII	Considerable deformations on buildings, cracks in bearing structure and walls, bigger cracks in partition walls, wrecking of factory chimneys, fall of the ceiling
24,0–48,0	IX	Wrecking of buildings, bigger cracks in walls, exfoliation of walls, collapse of some parts of the walls
greater than 48,0	X – XII	Bigger destruction, collapse of complete structures etc.

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As it can be seen from Table 1, damage on the buildings appears when oscillation velocity caused by blasting exceeds the IV level of the seismic scale. Damage on the buildings in poor condition can occurs during the shock with the intensity of the V level of seismic scale, while for buildings in good condition, the considerable deformations can only be expected during the VII level of the seismic scale. According to that, for the evaluation the seismic effect of blasting for buildings and other objects, it is necessary to take into account the condition of objects, the characteristics of soil as well as the number and method of blasting.

The permissible oscillation velocity for construction objects (residential, industrial, etc.) also depends on the type of object, its importance and purpose. Regarding that, all construction objects are divided into four classes.

I class. Especially significant objects of republican importance and architectural monuments. Blasting next to such objects is possible only in exceptional cases.

II class. Industrial facilities of exceptional importance: pipelines, large factory halls, hoist towers, water towers, and similar facilities; facilities whose useful life is longer than twenty to thirty years; residential buildings where a large number of inhabitants live, centers of culture, cinemas and similar facilities.

III class. Industrial facilities and administrative buildings of relatively small dimensions, the height of which does not exceed three floors; mechanical workshops, compressor stations and similar facilities; residential buildings where a small number of people live; warehouses, etc.

IV class. Buildings and industrial facilities where expensive machines and devices are located, and their damage does not endanger the life and health of people; warehouses, automobile bases, cold storage buildings, compressor stations, etc.

The permissible oscillation velocities in the foundation of objects, depending on object class, are given in Table 2.

Table 2 The permissible oscillation velocities in the foundation of objects depending on object class

Characteristics of the buildings and objects	The permissible oscillation velocity per object class, $v[cm/s]$		
	II	III	IV
Residential buildings and industrial buildings with reinforced concrete or steel construction, with light filling, calculated on seismic impacts. Satisfactory construction quality and without any changes in relation to the project and budget. There are no residual deformations in the construction.	5,0	7,0	10,0
Residential buildings and industrial buildings with reinforced concrete or steel construction. There are no residual deformations in the construction.	2,0	5,0	7,0
Buildings with partition walls made of brick or stone. New or old stone buildings or masonry buildings built without seismic influences. Good construction quality. There are no residual deformations in the construction.	1,5	3,0	5,0
Buildings that have significant wall damage and structural cracks. New or old stone or brick buildings with minor unconnected cracks in load-bearing and partition walls.	1,0	2,0	3,0
Old or new buildings with cracks and broken connections between individual elements. Stone or brick buildings with oblique cracks in load-bearing walls and corners, etc.	0,5	1,0	2,0
Damaged reinforced concrete construction, large cracks in the concrete. Buildings where the load-bearing walls have a large number of cracks, damaged connections between the external and internal walls, etc. Buildings built from prefabricated elements that are not seismically secured.	0,3	0,5	1,0

Criteria according to Russian scale for mining facilities. The level of rock mass deformation plays an important role in the protection of mining facilities constructed in a rock mass such as shafts, drifts, tunnels, rise headings, dip headings, chambers, stopes, sublevel posts, hydro-engineering tunnels, bench slopes, etc. Deformation characteristics of a rock mass have an essential impact while determining the threshold of deformations for facilities constructed in the rock mass (Lutovac et al., 2016). On the basis of experimental measurements, there have been established oscillation velocities of the rock mass in varied mining-geological and mining-engineering conditions whose values (Russian standards) are presented in Table 3.

Table 3 Description of occurrences in rock mass induced by seismic wave

Description of occurrences in rock mass induced by seismic wave	Oscillation velocity v $[mm/s]$
There are no damages	< 20
The occurrence of insignificant development of fissures induced by previous blasting; locally, falling out of single pieces along previously weakened surfaces.	20 – 50
Intensive development of existing fissures followed by minor caving of rock pieces with the dimensions to 0.2x0.2x0.2 m; the occurrence of cracks in tectonically weaker material filled fissures; the caving of bench slopes along tectonic deformations.	50 – 100
The development of tectonic fissures and the caving of rock pieces with the dimensions 0.5x0.5x0.5 m.	100 – 150
Caving from sides and roof of underground chambers along tectonic fissures, the formation of new fissures in undamaged part of the rock mass, collapse of safety pillars and benches.	150 – 300
Complete damage of sides and roof of chambers followed by large blocks with dimensions of 1x1x1m and filling up to the half of constructed surface; caving of hard rock slopes	300 – 400
Complete demolition of rock mass, the caving of large blocks bigger than 1x1x1 m and covering up more than a half of the chamber.	> 400

5.1.2 Criteria according to German DIN standard

These criteria prescribe the maximum permissible values of soil oscillation velocities, depending on the importance and condition of the objects, for oscillation frequencies of 5-100 Hz and for one to two blasting per day. The maximum permissible soil oscillation velocities are given in Table 4.

Table 4 Maximum permissible values for oscillation velocity v and oscillation frequency according to DIN

Maximum permissible values of oscillation velocity $\boldsymbol{v}[\boldsymbol{mm/s}]$				
Type of the structure	Foundation			Top floor ceilings
	<10 Hz	10–50 Hz	50–100 Hz	All frequencies
1. Structures used for craftsmanship, industrial and similar structural structures.	20,0	20,0–40,0	40,0–50,0	40,0
2. Residential buildings and structures similar in construction or function.	5,0	5,0–15,0	15,0–20,0	15,0
3. Structures that because of their special sensitivity to vibrations do not fall into groups 1 and 2 and are essential for conservation (for institutions as cultural-historical monuments).	3,0	3,0–8,0	8,0–10,0	8,0

Graphical representation of $DIN-4150$ standard, shock as a function of frequency, is shown in Figure 2.

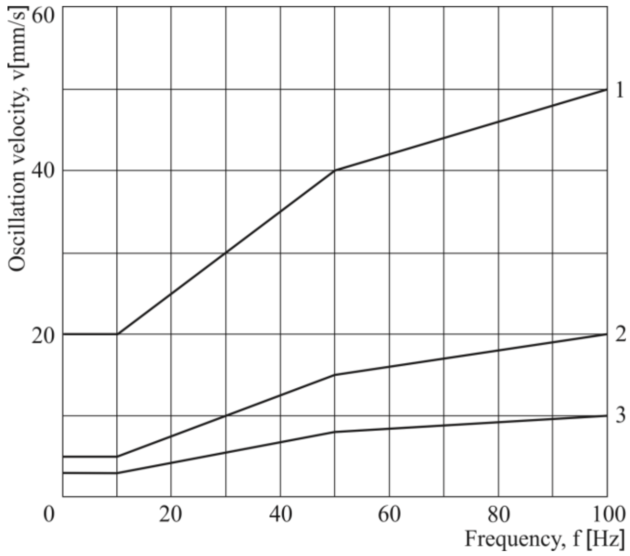

Figure 2 Graphical representation of $DIN\!-4150$ standard (1, 2 and 3-type of the structure) (DIN 4150-3:1999)

5.1.3 Criterion according to USA standard

The United States Bureau of Mines (USBM) has issued a standard (RI 8507-1980) for permissible oscillation velocities of residential buildings as a function of frequency. For residential buildings, the permissible oscillation velocities in the frequency range of $1-4\,Hz$ vary from $4-20\,mm/s$. In the frequency range of $11-30\,Hz$, the permissible oscillation velocities vary from $20-50\,mm/s$, and above $30\,Hz$ they amount to $50\,mm/s$. Graphical representation of the limit oscillation velocities is demonstrated in Figure 3.

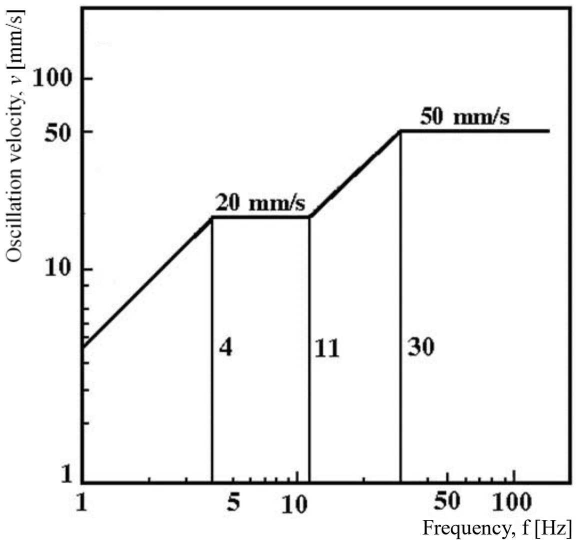

Figure 3 Graphical representation of the limit oscillation velocities - The United States Bureau of Mines RI 8507 (Siskind et al., 1980)

6 CONCLUSION

In the mining industry, explosives are primarily used to extract minerals from hard rocks. In the world today, explosives charges with a very large amounts of explosive are used which are capable to cause seismic shock of such intensity, which will a harmful effect on the environment and induce the displacement of objects.

In most countries, regulations have been adopted that regulate the level of shock caused by blasting, which can load buildings, depending on their importance, condition, and dynamic resistance. Such regulations have not yet been adopted for our country, so in solving this problem we use the regulations and norms of other countries, most often Russian, German and American.

In this paper, criterion of the IFZ Russian Academy of Sciences, criterion according to Russian norms for mining facilities, criterion according to German DIN standard and criterion according to USA standard are represented.

According to criterion of the IFZ Russian Academy of Sciences, the permissible intensity of shock for objects of different resistivity is related to rock mass oscillation velocity. The degree of seismic intensity is given in the form of twelve seismic degrees.

Criteria according to German DIN standard prescribe maximum permissible values of soil oscillation velocity, depending on the importance and condition of objects, for three groups of objects, for the frequency range of $5 - 100\ Hz$ and for one to two blasting per day.

Criterion according to USA standard prescribes the permissible oscillation velocities of the residential buildings in the appropriate frequency range.

Given that the regulations regulating the level of shock caused by blasting are in accordance with the seismic and geological conditions that are characteristic of a certain country, the necessity of regulating this phenomenon in our regulations is indicated. In this way, doubts would be avoided when evaluating the seismic effect of the explosion, which occurs because of blasting.

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