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Substantiating parameters of short-delay blasting and seismic safety while constructing the inclined tunnel

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Abstract. Implementation of blasting works in mining engineering and underground construction requires new effective blasting technologies in conducting an explosion. Short-delay blasting is a technology that requires scientific substantiation of its parameters. The application of explosion technology with increased blast intervals between charges is characterized as successful. However, the degree of reduction of seismic action and, accordingly, an increase in seismic safety needs clarification of the parameters of short-delay blasting. The scientific paper analyzes the delay time of the blast of charges and the classification of the degree of damage to buildings and structures. Seismic safety parameters for the inclined tunnel "Skhidnyi" while tunneling at the quarry of the Inhulets Ore Mining and Processing Plant (in the city of Kryvyi Rih) have been substantiated. The functional dependence of the maximum vibration velocity on the seismically safe distance has been obtained, as well as the dependence of the coefficient, the value of which characterizes the mass of the explosive. This allows for a quick evaluation of seismic safety parameters when calculating the parameters of blasting operations in the case of short-delay blasting.

1. Introduction

As it is known, according to the nature of the destruction process and its results, short-delay blasting (SDB) differs significantly from traditional methods of blasting operations [1]. The advantages of instantaneous and delay-action blasting methods for most mining conditions are successfully combined in SDB. This ensures an increase in technical and economic indicators and safety of work [2], which, in turn, significantly increases the ability to reduce the seismic effect of a blast with a high quality of rock crushing. All this together has made it possible to quickly and widely contribute to the widespread use of SDB in the mining and tunneling industry [3].

When using SDB, blast charges are fired sequentially at specified short time intervals, calculated in hundredths or thousandths of a second. This creates the necessary conditions for the interaction of charges. As a result of the fast process of a large-scale blast, the probability of undercutting neighboring charges is sharply reduced and the SDB safety in gassy workings is increased [4].

In line with the already obtained earlier results, it has been determined that SDB is more effective than when using instantaneous and delay-action blasting methods [3-4]. Also, SDB provides the most complete use of explosive energy. In addition, by appropriate selection of delayed action and blasting scheme, it is possible to control the action of the explosion and obtain the necessary results on the

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broken-rock disintegration and the direction of the seismic action.

Until recently, for the destruction of rocks for III-V fracturing categories (III – medium fractured (large rock fragments); IV – small fractured (microfragmental); V – almost monolithic) the degree of grinding [5] when using SDB is improved compared to instantaneous blasting [6]. At the same time, the best grinding result is achieved in those SDB schemes in which the largest number of charges are detonated at different times, and their action is directed toward each other. Due to this, the maximum interaction of waves and mechanical grinding of rock pieces is ensured.

The degree of grinding is influenced by the patterns and intervals of SDB, the orientation of the charges in relation to the systems of cracks, and other factors. In the specific conditions of underground workings, when choosing blast schemes, it is necessary to take into account both the degree of grinding and the conditions for the technical feasibility of their implementation and seismic safety [7].

The SDB also allows you to implement another effective way to control the grinding of a fractured massif by blasting hole charges along the contour of the working in proactive mode. In this case, the initiation of charges inside the block is carried out at short intervals, which, after the blast in proactive mode, leads to the closure of cracks. Here, the destruction of a massif with closed cracks is carried out more intensively due to a decrease in energy consumption during the transition of a shock wave and a stress wave through the crack planes [3, 4].

Thus, certain features of SDB testify to the fruitfulness in the application of this blasting method in mining and underground construction. It is emphasized that this method can significantly reduce the seismic effect of the blast on objects around the working, but requires additional research. The purpose of this scientific article is to substantiate the parameters of SDB and seismic safety during the construction of an inclined tunnel.

2. Methods

Substantiating the SDB parameters is based on the analysis of the physical and mechanical characteristics of the rock massif while blasting operations in open-pit and underground mining. However, a critical analysis of the already obtained data, especially those related to the quantitative indices of the SDB, indicates insufficient development.

Thus, according to the analysis of the given theoretical data, the calculation formula for defining the delay time during the SDB application of hole charges has the following form [1]:

$$t = t_1 + t_2 + t_3, \tag{1}$$

where t_1 – the time of bringing the massif into a stress condition before its destruction (it is 1 … 2 ms); t_2 – the fracturing time of the emission prism (it is estimated in the range of 14 … 21 ms); t_3 – the time calculated according to the condition of displacement, raising and separation from the massif of the emission prism by the following empirical formula [8]:

$$t_3 = 80 \cdot 10^{-6} \frac{\gamma W^2 \tan\left(\dfrac{\beta}{2}\right)}{d}, \tag{2}$$

where γ – is the specific weight of the rock (kN/m^3); W – the line of least resistance (m); β – the opening angle of the emission prism (grad); d – the diameter of the well (m).

The value of W for smooth blasting (using contour holes) is determined according to the empirical formula [4]:

$$W = 52kd\sqrt{\frac{\rho}{\gamma e \omega}}, \tag{3}$$

where k – the coefficient of the suppression, k=0.7 … 0.9; d – the explosive charge diameter (m); ρ – the density of the explosive (kN/m^3); e – the coefficient of an explosive equivalence, e=1.0; ω – the coefficient of structure and fracturing of hard rocks, ω=0.6 … 2.0 (ω=2 is for strong non-fractured hard rocks).

The time t_3, determined by the formula (2), is equal to 8 … 12 ms, and the total value of the delay time t on the free plane is 23 … 35 ms.

In the scientific and technical literature on the physics and mechanics of blast in hard rocks for many years, there is a doctrine about the following parameters of the SDB, which characterize its effectiveness:

– pressure reduction of the air shock wave;
– velocity decrease of rock pieces movement and creation of a compact pile of grinded rock mass;
– a significant increase in the intensity of hard rock grinding during the explosion;
– reduction of the seismic effect of a mass blast on objects located in the zone of action.

However, all these parameters are satisfied when applying delay intervals between cut holes, outside holes, and contour hole charges of 25 … 75 ms. At the same time, according to the analysis of seismographic hodographs obtained as a result of measuring vibration velocities during the construction of the Dnipro Metro [9], the given intervals led to wave interference and a significant increase in the amplitude-frequency characteristics of vibration processes during underground blasting operations.

However, even with the correct calculation of delay intervals, there is an important problem with seismic safety. When conducting blasting operations, damage to people, buildings, structures, and mechanisms in the zone of blasting occurs as a result of the action of seismic and air shock waves, as well as due to the scattering of fragments of rocks caused by the blast. According to the degree of damage, buildings and structures are classified as follows (table 1) [1].

Table 1. Classification of the damage degree to buildings and structures.

Degree of damage	Characteristics of damage
I degree	Whitewash crumbling, hairline cracks in the plaster. The bearing capacity of the building does not decrease.
II degree	Thin (up to 1 … 2 mm) cracks in the plaster. The bearing capacity of the building does not decrease.
III degree	Plaster chipping off, small (up to 2 mm) cracks in the walls. The bearing capacity of the building decreases (20 … 25 %).
IV degree	Numerous wide (more than 2 mm) cracks in the walls, destruction of walls, collapse of floor beams, etc. The bearing capacity of the building decreases significantly (30 … 70 %).
V degree	Complete destruction of the building, the bearing capacity of the structural elements has been exceeded.

From table 1, it is clear that for most buildings and structures violations of the III degree are unacceptable, and IV and V ones are emergencies. To ensure the operational condition for II-IV classes of buildings and structures, permissible vibration velocities should not exceed the values of 2 … 6 cm/s. To determine the safe charge per one delay in relation to a single seismically safe charge, in practice, the "two-thirds" rule is used, according to which, in one go, the charge value per one delay should be 2/3 of the seismically safe charge value.

To avoid seismic wave interference, it is necessary that the delay interval equals or exceeds the time in the positive phase of the seismic wave at the distance at which the protected object is located. In this case, conducting blasts of seismically safe series can be unlimited. The period of the main vibrations increases with the mass of the charge and the distance and is about 10 … 30 ms during the blast of a charge with a mass of 1 ton. This excludes the interference of seismic waves when using the SDB of hole charges. At the same time, the vibration periods are weakly dependent on the mass of the charge and the distance and are 0.15 … 0.4 seconds, i.e. 150 … 400 ms. Then the division of the total mass of blasting charges in one cycle into groups with delay intervals of 400 … 10.000 ms would lead to the complete exclusion of the interference of blast waves.

3. Results and discussion

As an example, the parameters of seismic safety for the inclined tunnel "Skhidnyi" during the tunneling in the quarry of the Inhulets Ore Mining and Processing Plant (Kryvyi Rih) have been substantiated. Spotting of the holes corresponds to the SDB conditions (figure 1) [10].

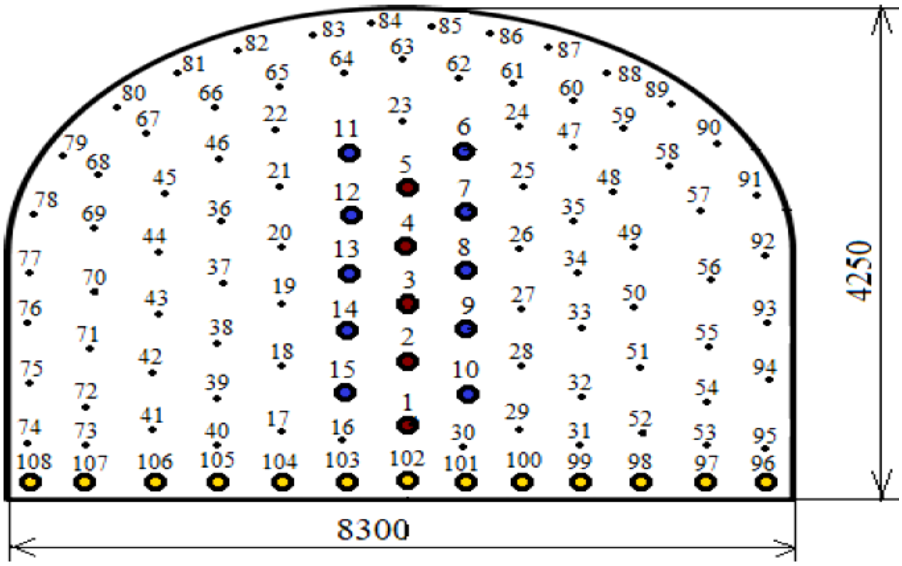

Figure 1. Spotting of holes for the inclined tunnel "Skhidnyi": 1-5 – empty holes; 6-15 – cut holes; 16-73 – outside holes; 74-95 – contour holes; 96-108 – bench holes.

When the SDB of N charges of total mass Q with a delay time between the blasts of each charge of at least 20 ms, the determination of the safe distance r (m) is performed according to the formula [8]:

$$r = K\alpha\sqrt[3]{Q}\,, \tag{4}$$

where K – the coefficient that depends on the properties of the soil at the base of buildings and structures protected from seismic action (for hard non-fractured rocks, K=5); α – the coefficient that depends on the blasting conditions (for excavation explosion is of α=0.8); Q – the total mass of blasted charges in the tunnel face (Q = 190.0 kg).

The calculated value is r = 23.0 m, but for further calculations with a certain margin, a safe distance of r = 30.0 m is accepted. The critical vibrations velocity (V_{cr}, cm/s) for the conditions when blasts are carried out in underground conditions is accordingly determined by the formula [1]:

$$V_{cr} = \frac{K_c}{\varepsilon}\frac{\sqrt[\beta]{Q_s}}{r}\,, \tag{5}$$

where K_c – the coefficient that depends on engineering and geological conditions (we accept K_c = 200); ε – the coefficient that depends on the conditions of blasting operations and the state of the engineering structure, ε = 1.5 … 3.0 (we accept ε = 3.0); Q_s – the seismically safe mass of charges for the conditions in which tunneling takes place (the calculated value is of Q_s = 190.0 kg); β – the coefficient that depends on the distance to the object, β = 1.5 … 2.0 (we accept β = 2.0). The engineering and geological conditions under which the inclined tunnel "Skhidnyi" passes are the following: 1) ferruginous quartzites; 2) fine-grained magnetite quartzites; 3) medium-grained magnetite quartzites; 4) magnetite-silicate quartzites; 5) talc slates. The strength according to the scale of Professor Protodiakonov for these rocks is f = 9 … 20 (the average range of rocks that are most common for the conditions of the Inhulets Ore Mining and Processing Plant is f = 14 … 16), that is, the rocks are characterized as strong and too strong.

The estimated value of V_{cr} = 5.6 cm/s, which, based on the analysis of permissible velocities for II-IV classes of buildings and structures, almost reaches the upper limit of 6 cm/s. Therefore, an analysis of the change in the critical vibration velocity V_{cr} from the distance r was carried out. The condition of the analysis is that the blast of charges of explosives with a mass of Q = 190.0 kg is simultaneously carried out at a minimum distance of 30 m.

Formula (5) for the conditions of the Inhulets Ore Mining and Processing Plant is not uniquely adequate. Conducted trial blasts indicate that the value of V_{cr} is most commonly significantly overestimated. This fact is explained by the increased strength of rocks according to the scale of Professor Protodiakonov. Therefore, formula (5) was corrected by changing the coefficient obtained from field observations and the new formulation of vibration velocity $V_{\max}$ as the maximum. So, the maximum vibration velocity $V_{\max}$ (cm/s) is defined for the obtained distance in line with the formula:

$$V_{\max} = 2.5\left(\frac{\sqrt[3]{Q}}{r}\right)^{1.5}. \qquad (6)$$

The resulting formula, which characterizes the scientific novelty of the paper, was experimentally verified at the underground facilities of the Inhulets Ore Mining and Processing Plant. It was applied in practice when recalculating the passports of drilling and blasting operations and correcting distance r. For this, formula (6) was illustrated by the graph (figure 2). The variation of the distance r is carried out and the dependency graph of the maximum vibration velocity V_{max} (cm/s) on the distance r (m) is obtained for four values of the mass of the explosive Q.

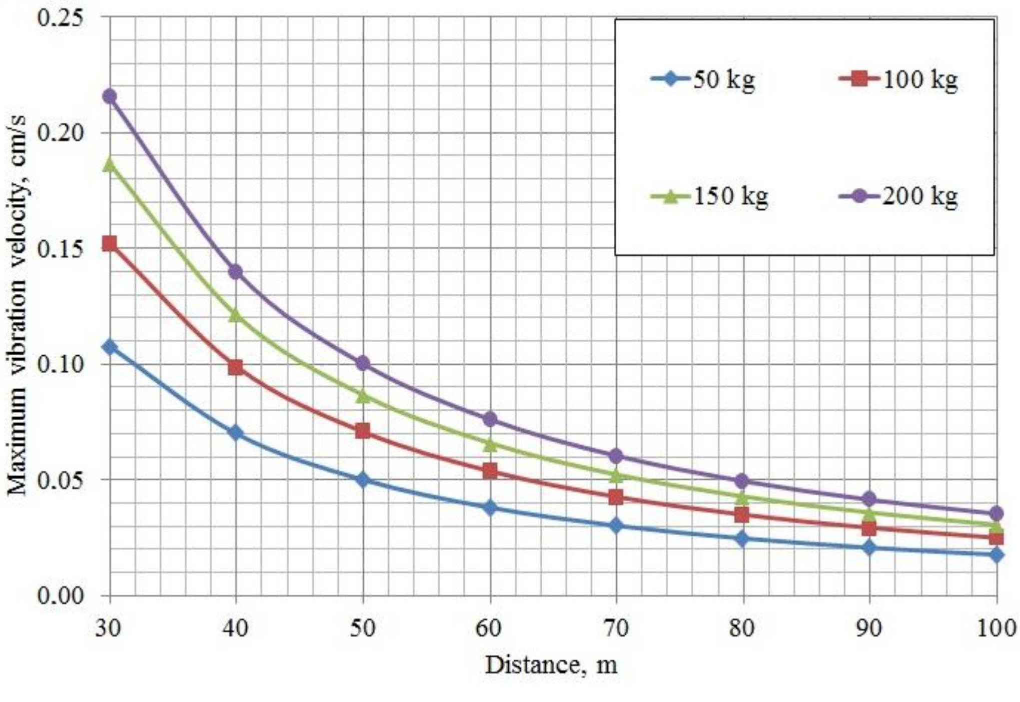

Figure 2. Dependencies of the maximum vibration velocity V_{max} on the distance r.

The practical application of formula (6) and figure 2 can be performed within the framework of direct and inverse tasks. In the first case, having the specific mass of the explosive Q, the maximum vibration velocity $V_{\max}$ should be set and the safe distance r should be found. In the second case, the safe distance r should be set and the corresponding maximum vibration velocity $V_{\max}$ should be found on the graph for all possible mass of the explosive Q. Illustration of the obtained dependence graphs proves that formula (6) can be simplified to the power-law form $V_{\max} = ar^{-1.5}$, where a – coefficient, the value of which characterizes the mass of the explosive Q. After analyzing the coefficients a, it is found that they change depending on Q according to a power-law trend $a = 2.5Q^{1/2}$.

The obtained power-law dependences of the maximum vibration velocity V_{max} and the coefficient a allow, without additional calculations, to obtain seismic safety parameters for all other values of the mass of the explosive Q. This greatly facilitates the evaluation of seismic safety parameters during the calculation for parameters of blasting operations. Having calculated the initial value of the mass of the explosive Q, it is possible by applying power dependences and graphs (figure 2) to correct its value upward (if the safe distance r allows it) or decrease (if the value of the safe distance does not provide the maximum vibration velocity V_{max}).

4. Conclusions

The article analyzes the features of short-delay blasting, which testify to the fruitfulness of the use of this method in mining and underground construction. The method of calculating the delay time of the blast of charges and the classification of the degree of damage to buildings and structures are considered.

Seismic safety parameters for the inclined tunnel "Skhidnyi" while tunneling at the quarry of the Inhulets Ore Mining and Processing Plant (in the city of Kryvyi Rih) is substantiated. The dependence of the maximum vibration velocity $V_{\max}$ on the seismically safe distance r is obtained. The obtained scientific results will allow a quick evaluation of seismic safety parameters when calculating parameters of blasting operations in the case of short-delay blasting.

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