

THE NEW APPROACH IN EVALUATING THE MECHANISM OF THE BLAST EFFECT AND ORGANIZING THE BLASTING OPERATIONS WHILE TUNNELING

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Abstract. It is relevant for the organization of blasting operations with consideration to the mechanism of blast effect to justify new provisions due to the emergence of new explosives, means of initiating charges and instrumental measurement of parameters. In view of this, a new approach is needed for evaluating the mechanism of blast effect in the combined application of short-delay and delay-action blastings with a high level of organization and safety. Analyzing the results in the justification of the short-delayed blasting, obtained by many researchers in recent decades, its main advantages and some limitations in its evaluation have been identified. A clear justification for the combined application under seismic safety is provided. New results to explain the mechanism of the blast effect in the combined application of short-delay and delay-action blastings at tunneling facilities have been obtained. They help in the seismic action reduction under the conditions of close city development. Methodological approaches to organize blasting operations at complex facilities in Ukraine implemented during tunneling have been developed.

Introduction. For many years, in the scientific literature on the mechanics of blasting there has been a doctrine about the advantages of short-delay blasting (SDB) in hard rocks in the opening driving, including tunnels, in all major positions: 1) increasing the intensity of crushing; 2) pressure decrease of the air shock wave; 3) velocity reduction of rock movement and creating a compact bulk of crushed rock mass; 4) reducing the seismic action of the blast.

Professor B. M. Kutuzov [1] pointed out the practical advantages of SDB, which were as follows: 1) more efficient use of blast energy; 2) higher quality of crushing the rock as a result of increasing its time in a stress state; 3) reduction of seismic action on the massif and better contouring of workings; 4) increase in the heading advance per round to shotholes length ratio. As it was established in this work, the expedient delay intervals between the cut holes and outside holes were 50... 75 ms, and between the outside and contour holes were 15... 25 ms, and with the increase of the rock strength, the delay interval decreased. The increased delay interval between the breaking-in charge and other charges, including outside and contour charges, is explained by the fact that the time of the rock breaking with the breaking-in charge, that is operating at one free surface, is greater than of the other charges.

Professor E. O. Mindeli in the monograph [2] considers the essence of short-delay blasting (SDB) and delay-action blasting (DAB). Moreover, the mechanism of blast effect at SDB is justified at an adequate level, but the physical meaning of DAB is not considered. It is noted that SDB method differs from DAB one is that the delay time between blastings of adjusting charges is much shorter.

Professor V. P. Kurinnoy in the monograph [3] pays great attention to the consideration of the rock destruction mechanism by borehole charges of DAB. At the same time, the issues of SDB and DAB while blasting the blast-hole charges, especially from the standpoint of systematic safety, have not been considered.

Efremov E. I. with his students in paper [4] presents the rock destruction mechanism at SDB is due to the increase in efficiency of all basic processes, including the breaking of rocks, the formation of cracks, rocks swelling and movement.

Polyankin G. N. discusses the essence of SDB in [5]. He states that SDB is widely used in mining operations, including the construction of tunnels and subways. It is noted that SDB provides the maximum rocks destruction while blasting with more uniform and high-quality crushing. This is explained by the interference of stress waves during the unsimultaneous action of multiple blasting (units of milliseconds are at small delay intervals), the formation of the additional exposure surfaces (at mean delay intervals is 14 ... 21 ms) and collision of soil pieces (at large delay intervals is 22 ... 50 ms) that flies apart.

The topical scientific and technical task for the organization of blasting operations, taking into account the mechanism of blast effect, is to justify the new provisions of this mechanism. In this regard, a new approach to the estimation of blast effect in the combined application of SDB and DAB with a high level of organization and safety needs to be developed.

Methods. When designing SDB, it is emphasized that with too little delay time between the blasts of charges of adjacent stages the shot rock does not have time to move towards the stope and clear the site for the next part of the shot rock. The motion speed of the shot rock is less at high values of the line of least resistance (LLS). Therefore, the sufficient time to form cracks and penetration of explosive gases into them will be correspondingly longer. U. Langefors proposed a ratio to calculate the delay time:

$$t = kw \quad , \quad (1)$$

where t – time in milliseconds; k – constant ($k = 3 \dots 5$); w – LLS, m.

Obviously, this dependence is true for long LLS and only for open operations. The analysis of many works on blast mechanics shows that some of them have separate references concerning DAB without the proper justification of the efficiency under certain conditions, including on seismic safety. It is noted that in order to determine the safest seismic charge that is blasting with a single delay, in practice, use the "two-thirds" rule. According to this rule, the charge value per single delay should be 2/3 of the seismically safe charge value that is blasting instantly in one go. It is also indicated that in order to avoid the interference of seismic waves, it is necessary that the delay interval be equal to or exceed the lifetime of the positive phase for the seismic wave. In this case, the number of sequence safe series that are blasting may be unlimited. It should be noted that the mechanism of such a process has not been considered and there are no proper theoretical provisions for the implementation of such blastings.

In case of blasting breaking, the SDB method performs a complex task related to obtaining the required quality of crushing, the necessary parameters in scattering of the blasted rock mass and ensuring the seismic safety for the protected objects.

Seismically safe mass of charges Q_{saf} (kg) for complex tunnel structures is calculated by the formula [6]:

$$Q_{saf} = r^3 \left(\frac{V_{cr} \varepsilon}{K_r} \right)^\beta, \quad (2)$$

where r – the distance to the object to be protected from the seismic blasting impact, m; V_{cr} – permissible critical velocity vibration ($V_{cr} = 20$ cm/s); ε – coefficient depending on the working conditions and state of the engineering project to be protected from the seismic blasting impact ($\varepsilon = 1.5 \dots 3.0$); K_r – coefficient depending on the engineering and geological conditions of the work; β – coefficient depending on the distance to the engineering project to be protected from the seismic blasting impact ($\beta = 1.5 \dots 2.0$).

Notably, the main factors that determine the effectiveness of SDB are the delay time between the individual blasting charges. At SDB there is a superposition and interaction of processes occurring in the rock at the moment of blasting, which is also dependent on the value of the delay time. At the same time, these intervals have a very small value of delay by 2... 5 and 5... 10 ms. These prerequisites confirm the hypothesis for the interference of stress waves at SDB, which leads to the production of the impulse amplitude in these waves and increase in action time of a positive phase.

Here we can find one contradiction in the evaluation of the interaction mechanism of stress waves since interference from the point of view of seismic safety plays a negative role. The analysis of the above and a number of other scientific works in the field of physics and mechanics of blasting does not allow to give a theoretical justification of the generality in obtaining positive effects only at SDB. Earlier, it was noted that the extended use of SDB was due to its advantages over instantaneous blasting and DAB. It was also emphasized that a higher level of efficiency and energy economy of explosives at SDB was safety and reliability while blasting the groups of charges with a delay of tens of milliseconds and a significant reduction in the seismic effect. It was also stated that the development and implementation of SDB and the corresponding technical means in "initiation" of charges made it possible to carry out drilling-and-blasting operations with a high level of quality and efficiency.

Results and discussion. In the recent decades, new results have been obtained upon the effective combined use of SDB and DAB, especially for tunneling facilities with a high level of seismic action reduction under the conditions of close city development and the availability of facilities requiring technogenic protection. It should be also noted that the present-day practice of blasting, despite the stability of the canons in evaluating the benefits of SDB for many decades, allows us to critically assess some of its positive factors, especially from the standpoint of seismic safety [5, 6].

For example, the following tunnel structures were excavated and constructed at the important facilities of Ukraine: 1) the dredging well and tunnels of the Dniester

hydroelectric pumped storage power station (HPSPS) [7]; 2) the workings of the Beskidsky two-track railway tunnel with a length of 1760 m, constructed using the New Austrian Tunnel Construction Method (NATM) [8, 9]; 3) two inclined shafts for a complex of the cyclical-and-continuous method at the Inhuletsk Ore Mining and Processing Industrial Complex, the length is 1000 m of each shaft [10]; 4) a part of the running tunnels of the second stage at the Dnipro metro. It should be emphasized that tunneling at the Dniester HPSPS was carried out in aleurolites and argillites with Protodyakonov scale of hardness $f = 4...8$, in Beskidskiy tunnel it was in aleurolites, argillites and sandstones $f = 4...8$, and at the Inhuletsk OMPIC for the inclined shafts tunneling was in jaspilite $f = 16...20$ and in running tunnels at the Dnipro metro it was in granites $f = 10...14$. In the course of blastings, the combined SDB and DAB were successfully used. At the same time, if the breaking-in charges blasted with a delay of tens of milliseconds, the part of the outside charges was in hundreds of ms, the rest of the outside, contour and bottom charges was more than 500 and even thousands of ms (up to 7...9 sec.).

During the blastings, measurements were made of all the basic parameters, but mainly of the seismic effect. According to the results of the measurements, all major processes, including crushing, generation of the air shock wave, rock scattering, and a level of seismic vibrations were all within the normal range.

It is particularly important to note that the study of seismic hodographs (dependences of the wave transit time on the source and recording coordinates) of seismic vibrations at the Beskidskiy tunnel and in the Dnipro metro demonstrate that, while blasting breaking-in charges and a part of outside charges there are interferential increasings of the amplitude-frequency characteristics. Further blasting of the remaining part of outside charges, as well as contours and bottom ones, the amplitude-frequency pulses were separated from each other on all studied hodographs in the complete absence of wave interaction and their interference (Table 1).

Table 1 – Indexes of the waves interaction in the combined SDB and DAB

The total charge mass in group Q , kg	Delay interval in the group t , c	Toatal delay, ms	The nature of the interaction		
			Hodographs superposition	Wave Interference	Vibration dumping
23	0 ... 0.35	350	present	present	insignificant
4.5	0.5 ... 0.6	100	weak	weak	strong
16.5	0.8 ... 1.2	400	absent	absent	strong
9.0	2.5 ... 2.8	300	absent	absent	strong
6.75	4.7 ... 5.2	500	absent	absent	strong
9.0	6.9 ... 7.4	500	absent	absent	strong

This is explained by the fact that while blasting of the next group of charges after 500...1000 ms and after 1.5, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0 and 9.0 seconds, the wave from the blasting of the previous group of charges, with the longitudinal wave

velocity in rocky soils, is several kilometers per second, will be by hundreds of meters and kilometers.

Measurement of velocity vibration while blasting along the running tunnel from shaft No. 14 at the Dnipro metro was performed using a Vibracord FX seismograph (A7 CHANNEL No. VA0480) and calibrated six seismic sensors. Three of these devices were set directly above the blasting focus underneath the ground at a depth of 40 m. Three others were also set on the surface at a distance of 25 m from the first group, and the distance from the blasting focus was about 50 m. In so doing, multiple blasting of blast-hole charges was conducting with a total mass of about 100...140 kg. The results of measuring the displacement velocities of soil particles on the surface were obtained (Table 2).

Table 2 – Displacement velocities of soil particles during explosions in the running tunnel, cm/s

Date of the blast	Seismic sensor numbers					
	1	2	3	4	5	6
26.01.18	0.319	0.184	0.156	0.204	0.155	0.138
02.02.18	0.231	0.181	0.084	0.467	0.266	0.250
09.02.18	0.130	0.112	0.169	0.083	0.042	0.146
16.02.18	0.306	0.161	0.166	0.166	0.218	0.403
02.03.18	0.141	0.170	0.087	0.258	0.131	0.125
07.03.18	0.289	0.221	0.168	0.333	0.204	0.221
20.04.18	0.659	0.157	0.462	0.728	0.329	0.169
02.07.18	0.254	0.298	0.165	0.147	0.276	0.185
23.07.18	0.287	0.292	0.216	0.327	0.315	0.171
13.09.18	0.531	0.209	0.391	0.276	0.395	0.253
20.09.18	4.973	3.379	3.434	0.343	0.299	0.180
26.10.18	0.205	0.339	0.300	0.297	0.269	0.173

As it follows from the analysis of the obtained data, the maximum displacement velocities of soil particles are 0.2...0.4 cm/s, which refer to I-II points of seismic vibrations, which are acceptable and safe indexes for buildings and structures of the IInd class, respectively. The exceptions are blastings of 04/20/18, and 09/20/18, conducted in granites with a high degree of water cut, at which the vibrational velocities achieved corresponded to the IInd and IIIId classes of buildings and structures of industrial or civil purposes with reinforced concrete or metal frame with filler, without antiseismic enhancements (achieved vibration rates corresponded to classes II and III of buildings and structures for industrial or civil purposes with reinforced concrete or metal frame with filler without anti-seismic reinforcements. It should be also noted that the vibration frequency is in the range of 30...102 Hz, the values of which exceed the values of the natural vibrations of buildings and structures and do not cause resonance phenomena in them.

Conclusions. As the practice in conducting the research blastings at the facilities of tunnel construction demonstrates, the combined use of SDB and DAB in difficult engineering-geological conditions can significantly reduce the seismic effect at underground blastings. At the same time, the requirements for the quality of crushing

rocks are provided without negative indexes of the charge lining that blast in groups with a value of delay of hundreds and thousands of milliseconds.

Instrumental researches in the combined use of SDB and DAB indicate the high efficiency of this combination and the new approach to evaluating the mechanism of blast effect and the organization of blasting operations while tunneling provides drilling-and-blasting operations of new development.

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