Ensuring environmental safety of massive explosions in the combined development of coal deposits in Kuzbass

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Abstract. The article discusses the issues of environmental safety during massive explosions at the open-pit mines of SUEK-Kuzbass JSC. In the paper, the parameters of drilling and blasting operations in the performance of massive explosions at the Zarechny open-pit mine are analyzed; the requirements for the calculation of seismically hazardous zones from explosions in the open-pit mine for underground mine workings of the Taldinskaya-Zapadnaya 2 mine are determined; the conditions of seismic safety of underground mine workings during explosions in the sections by means of instrumental measurements of the parameters of seismic-explosive waves (velocity, acceleration of displacement) are established; in the ShotPlus 5 program, the switching circuits of explosive networks are analyzed; the dependence of the maximum mass of charges that are simultaneously blasted on the distance is established, which ensures the seismic safety of underground mine workings; recommendations for determining the safe parameters of drilling and blasting operations in the sections are given.

1. Introduction
The extraction of minerals is accompanied by impacts of a different nature on the natural environment and humans. Typically, these can be air emissions, discharges into water bodies and, of course, changes in the composition of soil [1-3]. Blasting operations, being part of the production process, have always played and play a significant role in anthropogenic impact on ecosystems, creating a serious load on all components of the natural environment. It is worth noting that seismic vibrations caused by massive explosions are dangerous not only for objects that are on the surface, but also for underground mine workings, the destruction of which can lead to environmental accidents and disasters [4]. I.I. Kosinova et al. [5] note in their paper that “in a wide range of ecological and geological facts, a special place is occupied by the seismic effects of massive explosions, which, firstly, create the prerequisites for the occurrence of induced seismicity, and secondly, they excite seismic vibrations that affect the comfort of the living environment”.

In this regard, the issues of ensuring the seismic safety of underground mine workings (mine shafts, belt roads, etc.) become extremely important. The identification of these harmful effects and the determination of seismic safety is currently a very urgent problem [6, 7].

Under the seismic impact of an explosion, the cause of the discontinuity of the rock mass is a stress wave, the front of which is smoothed out in remote areas from the explosion site and gradually breaks up into two seismic waves, i.e., longitudinal and transverse vibrations. The seismic effect of an explosion and the factors that affect their intensity, namely the shape of the explosive charge, the type and mass...
of the explosive charge, the distance to the explosion site and the deceleration time, have been studied previously [8-11]. Numerous studies have been devoted to the study of the effect of seismic waves on mine workings, but the issues of the action of an explosion in fractured media are not sufficiently reflected therein [12-15]. As a rule, the state of the rock mass in the near-contour zone is assessed either by the combined action of static and dynamic stresses, or by the velocity of displacement of the particles of the medium behind the wave front. For the first approach to assessing the seismic stress state, a complex mathematical apparatus is required to be involved, and this approach is generally applicable to continuous homogeneous media. Therefore, in industrial seismology, experimental methods for assessing the seismic effect of massive explosions on mine workings are most widely used; as a parameter that characterizes the stability of the workings, the velocity of displacement of the particles of the massif behind the wave front (mass velocity) is taken. In this case, the critical mass velocity is such a value of the mass velocity at which the rocks on the excavation contour in the places of the highest stress concentration are in a state of limiting equilibrium, or a value, the excess of which leads to an increase in fracturing, i.e. an increase in the number of cracks and the degree of their opening.

The analysis of scientific works showed that the critical speed for various types of rocks in continuous media, which is measured on the free surface, varies from 0.6 to 2.8 m/s [16-18]. Practice [19-21] and our own measurements have shown that loose mine workings are damaged at much lower displacement speeds. The following main factors influence the stability of rocks around workings [22-24]: rock hardness; the degree of disturbance of the rock mass by cracks; the nature of the blockiness (the number of fracture systems); crack opening; crack filling; liquid content of rocks; orientation of cracks relative to the mine workings; span of mining; seismic effect of massive explosions; stress-strain state of the rock mass.

Experimental assessment of the level of seismic impact from massive explosions of the Zarechny open-pit mine on the mine workings of the Taldinskaya-Zapadnaya-2 mine and their comparison with permissible speeds, taking into account the coefficient of structural weakening of the massif, will make it possible to substantiate the seismic-safe parameters of blasting operations at the open-pit mine.

2. Materials and methods
The work is aimed at determining the safe parameters of drilling and blasting (blasting) operations during massive explosions at the Zarechny open-pit mine in terms of the impact of seismic impact on protected underground mine workings. The subject of research is the maximum possible amount of charge per deceleration stage, depending on the distance to the protected facilities.

The Zarechny site where open pit mining is carried out is located on the territory of the Prokopyevsky district of the Kemerovo region in the central part of the Erunakovsky geological and industrial region of Kuzbass; it is part of the Taldinsky coal deposit, within the Taldinsky 1-2 geological areas.

The parameters of the development system are presented in table 1 [25, 26]. According to the physical and mechanical properties, overburden and coal are divided into categories of excavation difficulty, drill ability and explosiveness as follows (table 2).

The practice established at the mine involves the use of the following explosives:

- To blast dry boreholes: Granulite UP-1; Granulite PS; Emulin.
- To blast weakly watered boreholes with a water column of 1-2 m: Emulin; a combination of waterproof and non-waterproof explosives.
- To blast heavily flooded boreholes: cartridges of Emulsolite P; Emulsolite A-20 in the form of emulsion explosive [27].

| No. | Parameter name                      | Value  |
|-----|------------------------------------|--------|
| 1   | Height of overburden ledge, m:     | 15.0   |
| 2   | Width of the working platform, m   | 40-44  |
| 3   | Width of the entry way, m          | 15.5-22.0 |
| 4   | Working angle of the ledge slope, degrees: | -      |

Table 1. Development system parameters.
Table 2. Properties of rocks by category.

| Name of lithological differences | Percentage of the total volume of rocks | Category according to the classification of Unified Production Rates For Geological Exploration (UPR) |
|----------------------------------|-----------------------------------------|------------------------------------------------------------------------------------------------|
| Quaternary deposits              | 100                                     | II, -, -                                                                                       |
| Bedrock                          | 100                                     | II, -, -                                                                                       |
| incl. sandstones                 | 18.4                                    | II- III, VIII, III                                                                           |
| siltstones                       | 61.3                                    | II- III, VIII, III                                                                           |
| mudstones                        | 0.4                                     | II- III, VIII, III                                                                           |
| coal                             | 19.9                                    | I, V, I                                                                                       |

The information provided in the Standard Design of Drilling and Blasting Operations at the Zarechny Open-Pit Mine of SUEK-Kuzbass JSC and Projects for Massive Explosions was analyzed to identify a number of shortcomings in how blasting operations are typically organized. “Despite the variety of design options, in practice, cut-off short-delay blasting schemes with a continuous borehole charge were often used to reduce the amount of rock breakdown during blasting. In rocks with a hardness factor f as high as 3-4.5 on the scale of Prof. M.M. Protodyakonov, the deceleration intervals in the short-delay blasting schemes were 25 ms.”[27]. The analysis shows that all of the above technical solutions do not help to reduce the seismic effect during massive explosions.

2.1. Measurement of parameters of seismic waves in underground mine workings

As part of the study, during the period from 16.09 to 20.09, 4 massive explosions were carried out at the Zarechny open-pit mine, 2 of which were directly above the field of the Taldinskaya-Zapadnaya-2 mine in the area of face 70-10 of seam 70. Seam 70 has a thickness of 4.2-5.7 m. The dip angle of the seam is 5-15°. According to the conclusion of KP VNIMI No.45 of 18.11.05, the seam is classified as a threatened reservoir in terms of rock bursts. The seam is classified as a threatened reservoir in terms of rock bursts from a depth of 210 m.

To measure the rate of ground vibration in the soil of a mine working, seismographs "ZET 7156-N" (velocimeter) and seismograph "ZET 7152-N" (accelerometer) were used (figure 1). This explosion-proof equipment is approved for use in gas-hazardous mines. It is included in the State Register of Measuring Instruments and is supported by valid verification certificates.

Figure 1. Digital vibrometer ZET 7156-N (seismograph).
The maximum value of the modulus of the total displacement vector serves as an instrumental estimate of the displacement velocity [28]:

\[ V = \sqrt{V_h^2 + V_t^2 + V_r^2} \]  

(1)

where \( V_h \) is the maximum vertical component, \( V_t \) is the maximum tangential component, and \( V_r \) is the maximum radial component.

The deeper the vibration velocity of the seismic wave attenuates more intensively than the wave that propagates along the earth's surface, which is confirmed by the results of measurements. Experimental measurements are carried out with the main purpose of obtaining a relationship between the mass of the simultaneously exploded charge mass and the displacement velocity vector.

2.2. Performing massive explosions

Blasting operations were carried out at block No.3u-203-19 seam 73 (figure 2). The rocks of the block are coals. These are easily explosive rocks, II - III explosive category. On the Protodyakonov's scale, rock hardness coefficient is 2. The total volume of the blasted block is 20,628 m³.

According to the project, the total mass of explosives (Emulsolite P-A-20-120) in the boreholes (excluding priming cartridges and IS) was 5,200 kg. The mass of the charge in the borehole averaged 104 kg. The number of boreholes on the block is 50. The grid of boreholes is 7x7 m, the diameter of the boreholes is 200 mm. The boreholes were about 7 m deep.

The DShE-12 was used for the installation of the surface and downhole blasting network. For deceleration, a pyrotechnic relay RP-E-2-42 with a deceleration of 42 ms was used. Explosive cartridges Blastit 90-3000 were used as priming cartridges. The total mass of priming cartridges was 150 kg. There were 6 boreholes per deceleration stage, or 642 kg of explosives (including priming cartridges). It should be noted that the actual location of the boreholes on the blasted block No.3u-203-19 differs from the design one.

According to the Conclusion of Industrial Safety Expertise No. 42-2009 in terms of risk analysis of mining operations and facilities, "Assessment of the seismic action of massive explosions of the Zarechny open-pit mine of SUEK-KUZBASS JSC on underground mine workings of the Taldinskaya-Zapadnaya-2 mine of SUEK-KUZBASS JSC for the guarded mine working (Parallel belt road) of the Taldinskaya-Zapadnaya-2 mine", with a distance of 140 m to the exploded block, the maximum mass of a charge in a group may not exceed 2,942.2 kg. According to the project, for a massive explosion at block No.3u-203-19 seam 73, the maximum mass of simultaneously exploded charges was 642 kg with a distance of 142 m.

![Figure 2. Diagram of the blasted block No.3u-203-19 (actual).](image)
Blasting operations were carried out on overburden rocks (sandstone, siltstone) at block No.3v-204-19 seam 73 (figure 3) and coal at block No.3u-205-19 seam 73 (figure 4).

In the field zone of the Taldinskaya-Zapadnaya 2 mine, blasting operations were carried out at block 3v-204-19 seam 73. Block No.3u-205-19 seam 73 did not get into the area of the mine field.

For block No.3v-204-19 seam 73, rocks are sandstone and siltstone. These are easily explosive rocks, II - III explosive category. On the Protodyakonov's scale, rock hardness coefficient is 5. The total volume of the blasted block is 80,441 m$^3$.

According to the project, the total mass of explosives (Emulsolite A-20 and Granulite RD) in the boreholes (excluding priming cartridges and IS) was 32,000 kg. The mass of the charge in the borehole was on average 142 kg: for boreholes charged with Granulite RD and 180 kg for boreholes charged with Emulsolite A-20. The number of boreholes on the block is 225. The grid of boreholes is 8x9 m, the diameter of the boreholes is 200 mm. The boreholes were about 7 m deep. Three rows of boreholes in the southern part of the block with a depth of 5 m. The mass of the charge in them was 110 kg (Emulsolite A-20 as the explosive used).

For the installation of the surface explosive network, a non-electric initiation system of the "Korshun-M" type DIN-P-176-10 and DIN-P-42-9 with decelerations of 176 and 42 ms, respectively, was used. For the installation of the downhole network, the "Korshun-M" type DIN-S-500-18 non-electric initiation system with a deceleration of 500 ms was used. Explosive cartridges Blastit 55-1000 were used as priming cartridges. The total mass of priming cartridges was 225 kg. Blasting was performed according to a borehole-to-borehole procedure. Initiation began from the northern part of the block. For one deceleration stage, 364 kg of explosives were used (including PC), the number of deceleration stages was 113 (according to the project). (Given that blasting was carried out on a borehole-to-borehole basis [29-31] with a deceleration interval between boreholes of 40-50 ms, one can say that 200 deceleration stages were made with a maximum charge mass of 364 kg per stage. This charge mass does not exceed permissible value (2,942.2 kg).
2.3. Installation of seismographs in underground workings
The seismographs were installed in the Parallel belt road (figure 5) at PK195 (velocimeter) and PK184 (accelerometer) pickets. The blue flag (figure 5) indicates the location of the seismograph "ZET 7156-N" (velocimeter) at the PK195 picket. The red flag indicates the location of the seismograph "ZET 7152-N" (accelerometer) at the PK184 picket.

The sensors were installed at distances as follows: velocimeter: 330 m to the long-range charge, and 160 m to the nearest charge; accelerometer: 320 m to the long-range charge, and 200 m to the nearest one.

On the way back, after dismantling the seismographs, in the area of the PK260-PK265 pickets, rock falls were found (presumably coal) from the roof of the mine, closer to the side. In some places, the support was damaged, and the rock fell on the belt in insignificant quantities. It cannot be concluded that the explosions under study were the cause of disturbances that were formed in the rock. It should also be noted that this section of the Parallel belt road was distanced from the blasting site sufficiently far to be out of the danger zone.

![Figure 5. Fragment of the consolidated mining plan with reference to the places where the seismographs were installed.](image)

2.4. Analysis of switching circuits
For a more detailed analysis of deceleration intervals and comparison of data with seismograms, the location of borehole charges [32-34] in the blasted blocks was simulated with certain structural parameters, and the switching scheme was constructed in the SHOTPlus 5 program [35, 36]. Thanks to
this software, the initiation scheme has been analyzed, the groups of charges in decelerations and their time intervals have been identified to form an array of simultaneous explosive masses of charges.

3. Results

Based on the deliverables of the analysis performed in the SHOTPlus 5 software program, the layout of the boreholes of block 3v-204-19 and the installation of the explosive network are presented (figure 6). Similar analyzes were also carried out for block 3u-205-19.

![Installation diagram for block 3v-204-19.](image)

Figure 6. Installation diagram for block 3v-204-19.

Figures 7 and 8 show the analyzes performed (deceleration isochrones and direction of displacement of the blasted rock).

![Isochrones of decelerations at block 3v-204-19.](image)

Figure 7. Isochrones of decelerations at block 3v-204-19.

![Displacement direction of the blasted rock mass of block 3v-203-19.](image)

Figure 8. Displacement direction of the blasted rock mass of block 3v-203-19.

All the main parameters that are necessary in order to determine the dependencies according to M. A. Sadovsky and derive formulas for determining the rate of soil displacement are presented in (table 3).

| Group of charges | Total mass (according to the project), kg | Nominal deceleration, ms | Distance to the velocimeter, m | Distance to the accelerometer, m |
|------------------|------------------------------------------|--------------------------|-------------------------------|-------------------------------|
| 1                | 642                                      | 0                        | 154.6                         | 267.6                         |
| 2                | 642                                      | 42                       | 163.6                         | 278.1                         |
| 3                | 642                                      | 84                       | 173.9                         | 289.0                         |
| 4                | 642                                      | 126                      | 184.5                         | 299.3                         |
| 5                | 642                                      | 168                      | 194.8                         | 309.2                         |
| 6                | 642                                      | 210                      | 205.0                         | 318.8                         |
| 7                | 642                                      | 252                      | 215.2                         | 329.5                         |
| Group of charges | Total mass (according to the project), kg | Nominal deceleration, ms | Distance to the velocimeter, m | Distance to the accelerometer, m |
|------------------|----------------------------------------|--------------------------|-------------------------------|-------------------------------|
| 8                | 428                                    | 294                      | 223.2                         | 338.2                         |
| 9                | 428                                    | 336                      | 228.7                         | 344.1                         |

Based on the presented histograms, it can be concluded that the maximum number of charges that can be exploded simultaneously is three, and the largest explosive mass at a time is equal to 364 kg, which can be compared with the design data. It should be noted that the largest single explosive mass of an explosive charge falls on boreholes with a charge mass of 182 kg each rather than on three simultaneously exploded charges.

3.1. Processing of data obtained from seismographs

The software “ZETLAB” was used to process the data obtained from seismographs. Figure 9 shows the data recorded by the accelerometer, which was installed at the PK195 picket, as a result of blasting operations at block 3u-203-19. The data obtained is filtered and analyzed along three axes (XYZ) to select afterwards the useful signal from the frequency spectrum (figure 10).

![Figure 9. Data recorded by the accelerometer as a result of the explosion at block 3u-203-19.](image-url)
The resulting signal (figure 11), which is obtained as a result of the geometric addition of the velocity vectors (or accelerations in the case of an accelerometer), is used to compare with the parameters of drilling and blasting operations.

A similar analysis was also made as a result of processing the data obtained from the velocimeter, which is installed at the PK210 picket (figure 12).
Figure 12. Data recorded by the velocimeter as a result of the explosion at block 3u-203-19.

Then the data were analyzed, which were obtained from an accelerometer (PK184) and a velocimeter (PK210) as a result of an explosion at block 3v-204-19 (figures 13, 14).

Figure 13. Data recorded by the accelerometer as a result of the explosion at block 3v-204-19.
Figure 14. Data recorded by the velocimeter as a result of the explosion at block 3v-204-19.

4. Conclusion
As a result of processing the data obtained, individual dependences were derived for each explosion, with account for the near and far zones (figure 15). Also, the dependence of the limiting mass of a group of simultaneously exploded charges on the distance was determined at an oscillation speed of 1 cm/s (table 4, figure 16).

Based on the plot, it can be concluded that the minimum allowable charge mass is 572.8 kg at a distance of 140 m, which is less than the currently accepted minimum allowable mass (2,942.2 kg at 140 m).

Figure 15. Dependency plots for each explosion.
Table 4. Calculation of the mass of simultaneously exploded charges at different distances.

| Total mass, kg | Distance, m | Total mass, kg | Distance, m |
|---------------|-------------|---------------|-------------|
| 572.8         | 140         | 2885.5        | 240         |
| 704.5         | 150         | 3261.4        | 250         |
| 855.0         | 160         | 3668.7        | 260         |
| 1025.5        | 170         | 4108.5        | 270         |
| 1217.3        | 180         | 4582.1        | 280         |
| 1431.7        | 190         | 5090.8        | 290         |
| 1669.9        | 200         | 5635.8        | 300         |
| 1933.1        | 210         | 6218.3        | 310         |
| 2222.6        | 220         | 6839.7        | 320         |
| 2539.6        | 230         | 7501.2        | 330         |

Figure 16. Dependency plots of maximum mass of a charge vs. distance.

4.1. Recommendations for ensuring environmental safety

To ensure safety for underground workings from the side of drilling and blasting operations at the Zarechny open-pit mine, the parameters of drilling and blasting operations are recommended to be adjusted. The proposed changes are aimed at reducing the mass of the explosive charge in the borehole and in the group of charges in accordance with the obtained graphical dependence (figure 16). Also, the following shall be done:

- measurements (monitoring) of the impact of seismic explosive waves on mine workings should be continued;
- a lithological-structural model of the deposit should be built and the main geological domains should be highlighted;
- a geomechanical block model should be developed with the calculation of the maximum charge mass for each exploded block;
three-dimensional numerical simulation should be performed, with account for the scope of cleaning works and laying out of safety workings;

the structural attenuation coefficient should be taken aboard when calculating the displacement rates.

For further research in order to substantiate the possibility of increasing the maximum allowable mass of the charge, the following is planned:

- to conduct experimental explosions using dispersed charges with downhole deceleration;
- to conduct experimental explosions using combined charges, placing explosives with a low detonation velocity in the bottom of the borehole.

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