Analysis of seismic safety assessment procedures for joint
development of coal deposits

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Abstract. The safety of mining and exploitation operations is an important factor that allows accident-free mining of mineral raw materials. To achieve this goal, the companies take various measures to reduce hazardous factors, which include blasting and distribution of seismic explosion waves as the phenomenon under consideration. The initial calculation for the reduction of hazardous factors is based on a specially designed procedure. Currently, there are no approved standard methods that could relate to impact of seismic explosion waves on the mounting of mine openings. Various researchers have developed procedures that have certain advantages and disadvantages. This paper presents the methods to assess seismic explosion impact during joint development of coal deposits, which are commonly applied in Russia. It shows the analysis of proposed methods and directions for further improvement of calculations of safe parameters of seismic explosion waves to mine openings.

1. Introduction
Coal deposits are generally developed by open or underground method. In Russia, there are deposits that are developed jointly. Taldinsk coal field located in the central part of the Erunakovsky geological and industrial district of Kuzbass is an example. Underground mining operations result in geodynamic processes that encompass overlying open-pit mining, causing surface subsidence [4]. Figure 1 shows the design open cut with protected openings and the boundaries of the coal open cut.

Blasting operations on open cuts are carried out using emulsion explosives with high detonation properties [1, 2, 5]. When operating by the open method, a deposit is developed by drilling and blasting [13]. The vertical distance from the mine openings of the open cut to the mine openings of the mine can be up to 70 m. The blasting operations affect the mounting of the mine openings due to the seismic explosive effect, which is subject to assessment. Up to date, an ample quantity of procedures have been developed to assess the seismic impact on mounting of mine openings [3], but it is extremely difficult to compare the results obtained.

The Russian practice regulates the vector value of the ground vibration velocity, while the foreign practice compares the components of the ground vibration velocity with the vibration frequencies. By applying the criterion for the components of ground vibration velocity, the foreign researchers underrate the seismic impact. Since this criterion was developed to ensure the absence of cracks in the plaster of buildings, its application to the mounting of the mine openings is impractical as the volumes of the explosive rock mass decrease and the performance of the mining enterprise decreases as well. In a number of papers, Russian researchers use the components of the ground vibration velocity in plotting
the Sadovsky’s formula, and so they believe that this value can be identified with the vector velocity of the ground vibration. From the point of view of seismic impact reduction, the transition from component-based velocities to vector velocity is a positive result, but this transition contradicts the physical nature of vibration and composition of values, while permissible mass of the blasting charge per stage decreases. Herewith, it may be necessary to adjust the parameters of drilling and blasting operations for high quality crushing of the rock mass [11, 12].

![Figure 1. Plan of mine openings and open cut.](image)

2. Materials and methods
In accordance with the requirements for industrial safety “Explosive safety regulations” p. 843 of the “Federal rules and regulations ...” (hereinafter FNiP), the seismic safety distance can be determined by the following formula:

\[ r_c = \frac{K_G K_c N^{1/4}}{Q^{1/3}} \]

where \( r_c \) - means the distance from the site of explosion to the protected building (facility), m;
\( K_G \) - means the factor depending on the properties of the natural ground in the protected building (facility);
\( K_c \) - means the factor depending on the type of building (facility) and neighbourhood pattern;
\( a \) - means the blasting conditions factor; and
\( Q \) - means the mass of charge, kg.

The factors included in the formula (1) are descriptive in nature and are not determined based on actual physical and mechanical properties of the ground. Moreover, they do not take into account the structural features of buildings and facilities; that prevents from choosing the appropriate value for mounting of mine openings. The factor values used (type of building) refer to surface structures rather than to underground ones. At the same time, the overall level of seismic impact by the ground vibration velocity with the maximum allowable value is not assessed.

The rock structure of the mine openings consists of the following elements:

1. The roofing of the conveying shaft along the bed 70 is fixed with 2.75 m long steel-polymer anchors of 20 mm in diameter (rapid solidification ampoule L = 1000 mm – 1 pc., and slow solidification ampule L = 1,000 mm – 1 pc. is used as a binder) with the use of 5.1m long roofing plates made from a multi-grooved profile with 6 holes for anchors.
2. The sides are fixed with anchors, ampoules with hardening compounds, and washers. The length of the anchor is taken as 1.8 m. After a borehole has been drilled, an ampule is inserted; the corrugated end of the anchor is delivered to the bottom of the borehole and the jumbo is turned on to mix the ampoule content. After the mixture has hardened, a chain-link mesh is put on the anchor and secured with a washer and nut, which is screwed onto the anchor. The installation step of anchors is 1.0 m. The upper anchor is installed 0.3 m from the roofing.

Currently, the main document of the FNiP on industrial safety confers no possibility to assess seismic and explosive impact using a uniform procedure. However, it indicates that if the blasting conditions are not stipulated by FNiP, and the seismic impact of explosions should be determined with the engagement of specialized companies. A number of companies use the procedure developed by Magnitogorsk State Technical University [9]. According to the recommendations of Magnitogorsk State Technical University, the assessment of the seismic safe velocity is based on the formula for determining the allowable ground vibration velocity:

\[ v = 0.01 \exp(\sqrt{\exp(K - P)}) \]  
(2)

where \( K \) - means the facility criticality level, and \( P \) - means the protected facility rank.

Facility criticality level goes from 1 to 4, while the protected facility rank [9] is as follows:

\[ P = 14.54 - \lg(Cp) - \Delta kr, \]  
(3)

where value \( \Delta kr = 0.64 \) is the bolt anchorage correction. When using the formula (3) in calculations in order to estimate the rank of mine openings for actual velocity of sound propagation in solid in the range from 2,000 m/s to 5,000 m/s, the rank is always positive, and the value is over 10, which leads to a negative difference \((K - P) < 0\). Using levels and ranks entails the need for the researcher to choose among the proposed options the one that is most relevant in terms of the characteristics of the facility under consideration. Thus, the researcher can either overestimate or underestimate the value of the seismic safe velocity. Relationship (1) has two asymptotes with \((K - P) \rightarrow -\infty, v \rightarrow 0, \) with \((K - P) \rightarrow 5, v \rightarrow \infty\). In case of \((K - P) = 0\) difference, the function tends to increase (Figure 2).

![Figure 2. Relationship (2) expressed graphically.](image)

Therefore, the proposed relationship (2) can be applied in the range of \(2.5 < (K - P) < 4.2\). For underground openings, this range is achievable only with a negative rank of the protected object. It should also be noted that relationship (2) does not describe the combined stress state that occurs when
exposed to a seismic blast wave.

The other procedure applied to assess safety of the underground structures is given in paper [10] and involves formula:

\[
V = 18.510^{-7}C_p e^{2.3/1.16^{-T}},
\]

where \(C_p\) means longitudinal wave velocity, m/s; and \(T\) means workings operating time, years.

However, application of formula (4) entails the overestimated value of the maximum permissible velocities of the ground vibration of mine openings and does not take into account the mounting method.

The procedure proposed by paper [8] is also in use. For highly essential structures with a long service life of more than 10 to 15 years (shafts, permanent galleries, drainage systems), the allowable volumetric deformation is 0.0001. The maximum allowable velocity can be calculated by formula 5:

\[
V = \frac{0.375(C_p^2 + 4/3C_s^2)(1+(1-2v)\varepsilon_0)^{8/3-1}}{C_p[1+(1-2v)\varepsilon_0]^4} \cdot 10^2,
\]

where \(C_p, C_s\) means p and s wave velocities, \(v\) means the Poisson ratio, and \(\varepsilon_0\) means the volumetric deformation.

There are a number of guidelines with tabulated limiting ground vibration velocities for underground structures. In accordance with the "Guidelines for designing and performing blasts in the construction of underground structures" [6] «Assessment of seismic impact level», allowable vibration velocities for highly essential underground structures with a life over 10-15 years (Class 1 facilities) for these mining and geological conditions range from 4.5 cm/s to 6.3 cm/s. For less essential underground structures with a life of 5 to 10 years (class 2 structures), the allowable velocity can be increased to 9.4-13.2 cm/s. When applying the procedure described in paper [7], the maximum allowable velocity will be 4.3 cm/s.

3. Conclusion

When calculated by different methods with regard to same mining-geological and mining conditions, the range of allowable velocities can vary from 3 cm/s to 15 cm/s, which, in turn, will change the maximum allowable explosive weight from two to four times. With relation to the application of engineering practice for determining the seismic safe velocity, the procedure according to formula 4 described in paper [7] should be used. Since it contains the idea of elastic energy accumulation in a rock (energy hypothesis of failure), according to which, having reached a certain amount of elastic energy, the existence of separate parts of the rock becomes more reasonable than the existence of a whole volume. In the future, the initial volume of the body fails, while the accumulated energy is spent on formation of new surfaces (to create cracks). This idea makes it possible to calculate the seismic impact when using bolt anchorage in the mine openings. Since the hinge part of the anchor is in the virgin rock mass, and is attached to the rock by hardening mixture. If the rock in the hinge part starts to fail, the anchor will no longer hold the roofing of the mine openings. The practice shows that the anchor itself cannot be destroyed by seismic impact. Therefore, the maximum allowable ground vibration velocity should be set at a distance from the hinge part of the anchor away from the roofing of mine openings.

It is also essential to develop common guidelines for assessing seismic explosion impact on mining, which will reflect engineering procedures and mathematical modeling methods, the results of which will become the basis for deciding on seismic safe parameters of drilling and blasting operations.

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