Determination of Seismic Safe Distances During Mining Blasts with Consideration of a Dominant Vibration Frequency

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***Abstract* — A method for determining seismic safe distances for blasting operations in mines, taking into account the value of dominant frequencies of the earth surface vibrations is proposed. The method is based on a regression analysis of the experimental data; the method is characterized by a familiar and simple structure. The safety factor used as a criterion for seismic hazard is the ratio of peak particle velocity to its maximum allowable value adopted by the regulations, taking into account the dominant frequency. Instead of peak particle velocity, other parameters of vibrations may be also used, for example, the maximum ground displacement. It is also allowed to use mixed criteria of seismic hazard. The regression quality is evaluated using the statistical analysis of residuals. The method is based on the analysis of experimental data and therefore takes full account of both the particular way of performing blasting operations at a particular mining company, and the geological and hydrological conditions in the path of seismic wave propagation.**

***Keywords* — Blasting operations; seismic safety; regression analysis; the dominant frequency of the vibrations; open pit mining; mines and quarries.**

I. INTRODUCTION

The problem of seismic safety of buildings and structures for blasting operations in mines, in spite of the fairly large number of studies in this area (for example, [1-5]), is still relevant.

Federal rules and regulations [6] validated recently retained quite serious limitations in their application which had been characteristic to the previous versions of regulations in force in the territory of the Russian Federation. Thus, for example, instructions are given for determining seismic safe distances during non-simultaneous blasting of N charges with the total Q weight, while delays between blasts of each charge should be at least 20 ms. If a delay between blasts of separate charges is less than 20 ms then a group of such charges should be considered as a separate charge with the total weight for the entire group. Such an approach was used in blasting by rows using a detonating cord and delays between the individual rows of charges and was quite adequate for blasting technologies implemented then. However, mass transfer to nonelectric blasting with inter-hole delays made use of the instructions [6] impossible. In these cases, the time interval between blasts of each blast hole charge may be significantly below 20 ms. In such cases, the regulations developers recommend to turn to specialisedorganisations. Those specialized organizations tend to develop their own opinions based primarily on the results of experimental studies at specific mining enterprises. As a criterion for seismic safety, the following inequality is commonly used $v \le v_{lim}$. where$v$ – predicted peak particle velocity in the foundation of the protected object, and v_{lim} – the maximum allowable peak particle velocity for buildings and structures. Then, known relationships between peak particle velocity v, distance from the unit to be blasted to the protected object R as well as the weight of explosive in the conventional group of charges Q:

$$v = a \cdot \left(\frac{R}{\sqrt[3]{Q}}\right)^{b} \tag{1}$$

Here a and$b$ are evaluations of regression parameters obtained as a rule by the least square method following the results of experimental studies. In blasting practice, the largest explosive weight within sliding time 20-ms window is taken as Q.

It should be noted that several types of relationships slightly different from (1) are used in different countries. Thus, for example, in the USA, the UK and a number of other countries [7–9] a square root is used in the denominator and not a cube root, and Q is determined not by 20-ms but by 8-ms sliding time window. As it was shown in [10], there is no principal difference between the kind of regression relationship linking vibration velocity with blast parameters and a distance to the protected object. Differences in the method of presentation of a regression kind have an impact only on the values a and b themselves without any impact on the reliability of predicted particle velocity. The Russian regulations [6] recommend taking the values of maximum allowable peak particle velocity v_{lim} with consideration of regulations of other countries [8,9,12].

The described approach combined with a number of statistic evaluations of prediction reliability allows to predict the peak particle velocity at a set reliability level [13]. However, such an approach does not take into account an important circumstance that the value of the maximum allowable peak particle velocity v_{lim} depends on the dominant vibration frequency. In [14] in some cases, the need of taking

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this circumstance into consideration was shown via examples of several mining operations using various blasting techniques. In view of the above, the task has been set forth as follows – develop the technique for determination of seismic safe distances having a common structure but, at the same time, taking into consideration the dominant vibration frequencies.

II. MATERIALS AND METHODS

Recording of mining blast-induced seismic vibrations was made by InstantelMinimate Plus, InstantelMicromate geophones as well as by standalone units comprised of three-channel 24-bit seismic recorders Baikal AC with discretion frequency up to 600 Hz, seismic station Angara and seismic receivers A1632 and A1638 with a working frequency range 0.1–200 Hz and 0.1–400 Hz respectively.

Processing of seismic signals received at the geophones was performed using Blastware 10.74 software (Instantel). Processing included analysis of initial seismic signals, obtaining of the oscillation frequency spectrum by fast Fourier transformation (FFT) method. In some cases, also the primary signal processing was carried out to remove low-frequency components associated with signal distortions in the routes of the equipment.

Processing of seismic signals obtained with the help of "Baikal-Angara" complexes was performed in a similar way in Mathcad environment. Primary accelerogramswere integrated and low-frequency components were removed using the technique of [15]. Frequencies spectrum was also obtained using FFT.

To build regression the method of least squares (OLS) was used. The number of data points was in line with the possibility of constructing confidence intervals for the regression line with 0.95 reliability.

III. RESULTS AND DISCUSSIONS

To take into account the dominant frequencies, the safety factor is introduced for the *i*-th observation point KS_i:

$$KS_i = \frac{v_i}{v_{lim,i}(f_d)} \tag{2}$$

Here v_i – peak particle velocity recorded in the *i*-th observation point; $v_{lim,i}(f_d)$ – the maximum allowable peak particle velocity with consideration of the dominant vibration frequency f_d obtained for the *i*-th observation point. The safety factor value KS_i was taken as equal to the highest value obtained for each of the components x, y, z:

$$KS_i = \max\left(\frac{v_{x,i}}{v_{lim,i}(f_{x,d})}; \frac{v_{y,i}}{v_{lim,i}(f_{y,d})}; \frac{v_{z,i}}{v_{lim,i}(f_{z,d})}\right) \tag{3}$$

With this approach, the values $KS_i \leq 1.0$ correspond to safe levels of vibrations in the *i*-th point, and the values $KS_i > 1.0$ indicate an excess of allowable vibrations level.

An additional advantage of this approach is that it allows the use of mixed criteria in a single regression. For example, in [9] the peak vibration velocity is used as a seismic hazard criterion only if the dominant vibration frequencies exceed 4 Hz. At dominant frequencies below 4 Hz, ground displacement not exceeding 0.6 mm is used as a seismic hazard criterion. The presence of the mixed criteria does not allow the use of a unified regression to predict the seismic hazard.

The next step is regression analysis and calculation of the upper limit of the confidence interval for the regression line allowing to link the values of safety factors with the distance to the object to be protected and the weight of the explosive in a sliding time 20-millisecond window. By limiting the value of the safety factor by KS=1.0 and, knowing the distance from the boundary of the block to be blasted to the object to be protected, it is possible to set the limit value of the maximum charge in 20-ms window.

Here is an example of the proposed approach for the analysis of seismic safety used in the Erunakovsky field of Taldinsky open-pit mine (OAO UK Kuzbassrazrezugol). All the analyzed blasts were carried out with the use of Iskra (Spark) non-electric initiating system. Blasting parameters for the recorded blasts at this open-pit coal mine are shown in the table.

TABLE .BLASTS CHARACTERISTICS

Blasting method, inter-hole delays	**Typeofenclosingstrata**	**Range of total explosive weights in a block, TNT equivalent, kg**	**Weight of explosives and number of blast holes within sliding 20-ms window, kg**	**Number of conventional groups of charges**
Iskra non-electric detonation system; inter-hole delays of 25 and 67 ms	Siltstone (hardness 5-6),sandstone (hardness 7)	20443–145491	425,5–8220,8	4–123

A total of 10 blasts (144 three-component seismograms) were analyzed. Maximum allowable particle velocities depending on the dominant vibration frequency v_{lim}were taken as in [8]. The regression was built and the upper limit of the confidence intervals with 0.95 reliability. The regression parameters were estimated using the least square method. The estimated regression equations based on the width of the confidence interval were as follows:

$$KS = 178.23 \cdot \left(\frac{R}{\sqrt[3]{Q}}\right)^{-1.436} \tag{4a}$$

or

$$log_{10}(KS) = 2.251 - 1.436log_{10}\left(\frac{R}{\sqrt[3]{Q}}\right) \qquad (4b).$$

The determination factor for the regression model was 0.8.

The regression and the estimated upper limit of the regression confidence interval are shown in Fig. 1.

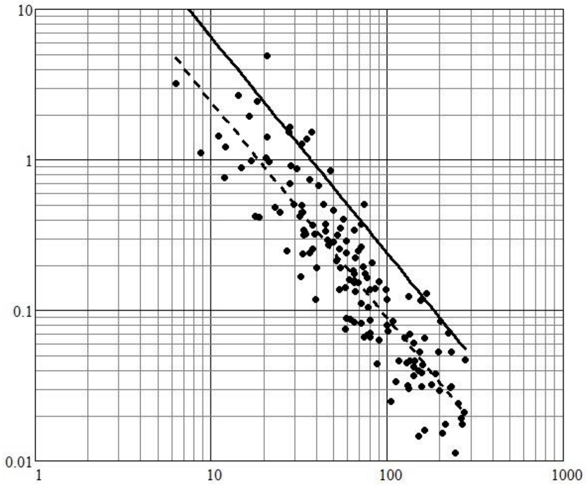
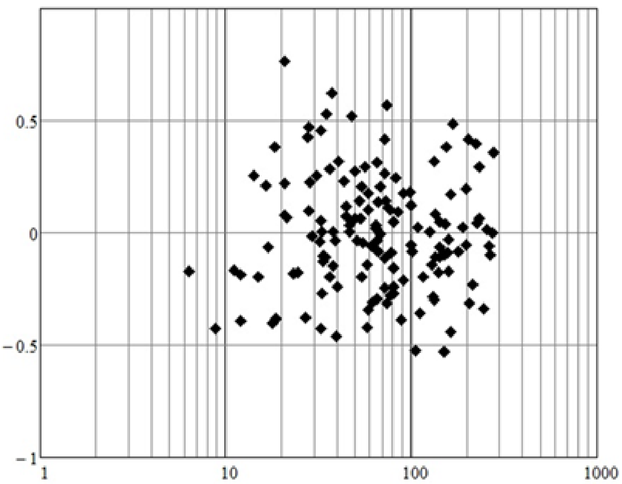


Fig. 1. Regression line (- - - -) and upper limit of confidence interval (——) with 0.95 reliability. The x-axis values are $R/Q^{1/3}$, the y-axis values are KS

Regression quality obtained using OLS was further evaluated using statistical analysis of residuals [10,13]. Under residuals, occasional deviation of the logarithms of the observed values KS_i from the logarithms of the regression values at the same points are meant. Durbin-Watson test has shown that there is a certain residuals autocorrelation in the model (the value of the Durbin-Watson statistic was equal to 1.14 at the lower and upper critical values equal to 1.61 and 1.65, respectively). The practice of the seismic safety analysis at a large number of mining operations shows that avoiding of the autocorrelation of the regression residuals is usually not possible because in most cases in the conditions of operating mines researchers are limited both in the parameters of explosions and in the choice of places to install seismic recorders. In the presence of autocorrelation, linear regression model while remaining unbiased and consistent ceases to be effective, i.e. variance, in this case, is not the smallest.

Residuals check on homoscedasticity (residuals dispersion consistency) over the entire interval of the explanatory variable was performed using Spearman's rank correlation test, the value of statistics for which amounted to 0.24. The critical value at the significance point of 0.05 was 1.656. Hence, the variance may be considered constant over the entire interval $R/Q^{1/3}$.

Also, in accordance with the terms of Gauss – Markov the regression model was checked on independence of residuals from the explanatory variable. Testing showed no such correlation, see Fig. 2.



. Fig. 2. Checking independence of residuals from scale distance $R/Q^{1/3}$. The x-axis shows scale distances $R/Q^{1/3}$. The y-axis shows residuals.

Also compliance of the actual distribution of residuals to the normal law was verified. ThetestresultsareshowninFig. 3.

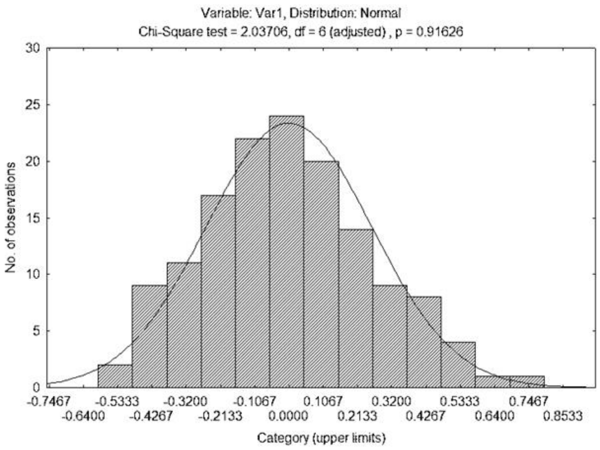


Fig. 3. The result of testing for compliance of actual residuals distribution with the normal law

Given all the above, we can assume that the regression model of the safety factor is quite consistent with the practical purposes of seismic safety prediction.

IV. CONCLUSION

1. The proposed approach of using safety factors allows to adequately take into account the value of the dominant vibration frequency. The method is simple and has a transparent and familiar internal structure.

2. The reviewed method allows the use of mixed seismic hazard criteria under which in one range of dominant frequencies peak particle velocities are used as a parameter indicative of vibrations hazard, while in another range of frequencies ground displacements are monitored.

3. The method is based on experimental data and therefore fully takes into account the peculiarities of blasting at a

particular mining operation as well as geological and hydrological conditions in the path of seismic wave propagation.

4. Recording of dominant frequencies allows to eliminate assessment of seismic hazard by one, the most unfavorable dominant vibration frequency. This makes it possible to extend the operating range of blasting parameters without reducing the level of seismic safety.

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