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Principles for classifying explosive seismic sources using the USBM formula

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Abstract
This article examines the seismic effects of blasting operations on protected structures, highlights the importance of this factor for ensuring occupational safety at mines, and reviews advances in predicting the magnitude of seismic effects. The relevance of applying two classical formulas, Sadovsky's formula and the USBM formula, is substantiated for predicting the parameters of blast-induced ground vibrations. As the problem of classifying blasting operations according to their seismic effect has already been solved using Sadovsky's formula, the present study addresses a similar classification problem for the USBM formula, given its widespread use in international practice. The problem was solved based on a statistical analysis of paired values of the seismic coefficient and attenuation exponent for blast-induced ground vibrations, compiled from open literature sources. For the first time, the attenuation exponent is shown to follow a normal distribution, while the seismic coefficient follows a lognormal distribution; the key parameters of these distributions are also estimated. A classification criterion is proposed for explosive seismic sources based on their seismic impact level, distinguishing between high and low seismic effects. The statistical significance of the paired regression is evaluated, leading to the conclusion that the coefficients in the classification criterion are statistically significant. Challenges associated with classifying explosive seismic sources by seismic impact level are discussed for both the USBM and Sadovsky's formulas. Practical examples are presented to demonstrate the application of the proposed classification for the comparative assessment of seismic effects generated by different explosive sources. Directions for further research are also outlined.

Keywords
blasting operations; blast-induced ground vibrations; peak particle velocity; USBM formula; statistical distributions; protected structures

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Introduction

Blasting operations are widely used in mining and construction for the efficient fragmentation of hard and moderately hard rocks, and it is unlikely that a viable alternative will emerge in the foreseeable future [1, 2]. However, the release of explosive energy is accompanied by adverse effects of blast-induced seismic waves on protected structures, including quarry slopes and benches [3], operating gas pipelines [4, 5], underground mine workings subjected to surface blasting, surface infrastructure [6-8], process equipment [9], transport tunnels [10], and others. A relationship has been established between the frequency of induced seismic events and the explosive charge mass based on observations from Kuzbass open-pit mines. Furthermore, a causal link has been identified between bulk blasting and induced seismicity [11, 12]. This issue becomes particularly critical when mining deposits prone to rock bursts [13]. Consequently, the design of blasting operations that ensure safe levels of ground vibration at the foundations of protected structures is a key engineering challenge.

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Modern approaches to blast design include the use of numerical modeling algorithms [14-16] and machine learning methods [17-19]. Analytical prediction models [20-22], which are an essential component of mining engineering education, remain relevant today [23]. However, these approaches have the following limitations: the use of complex mathematical tools inevitably leads to the need to make numerous assumptions about the modeled impact on the structure; machine learning methods depend on large datasets covering a wide range of blasting conditions; and analytical models often involve empirical coefficients with significant uncertainty and, in some cases, unclear physical interpretation. These limitations restrict the reliability of predicting blast-induced vibration levels at the early stages of mining. Therefore, classical formulas used in blasting practice for predicting peak particle velocity (PPV) remain highly relevant:

$$\upsilon = K(\bar{R})^{-n},$$

where K is the site-specific seismic coefficient; n is the attenuation exponent; $\bar{R} = \frac{R}{\sqrt[3]{Q}}$ is the reduced distance from the blast to the point of interest (Sadovsky's formula); $\bar{R} = \frac{R}{\sqrt{Q}}$ is the reduced distance from the blast to the point of interest for a spherical charge (USBM formula); R is the distance, m; Q is the explosive charge mass, kg.

A previous study [24] established a functional relationship between the attenuation exponent and the seismic coefficient in Sadovsky's formula. Statistical distributions of these parameters were obtained, and a classification of explosive seismic sources based on their vibration impact level was developed. These results significantly improve the reliability of predicting blast-induced ground vibrations, even when only limited field data are available.

Given the widespread application of the USBM formula, it is relevant to conduct similar studies to establish statistical patterns among the parameters included in the USBM formula.

Methods

The proposed research methodology comprises the following stages:

• collection of paired values of the seismic coefficient K and attenuation exponent n from published experimental studies conducted under a wide range of blasting conditions;

• statistical analysis of the individual distributions of the parameters included in the USBM formula;

• derivation of a classification criterion, defined as a relationship between the attenuation exponent and the logarithm of the seismic coefficient, enabling the classification of explosive seismic sources into categories of high and low seismic impact;

• evaluation of the statistical significance of the parameters in the proposed classification criterion.

The classification criterion is derived by solving an optimization problem that minimizes the root-mean-square deviation between the envelope of the measured peak particle speed and the envelope predicted by the USBM formula, with both envelopes subjected to identical low-pass filtering. This approach has previously been applied to develop a classification criterion based on Sadovsky's formula and to establish a classification framework for explosive seismic sources. In international blasting practice, predictions of PPV values using both Sadovsky's and USBM formulas are often performed concurrently when analyzing the same experimental data. Thus, the methodology is based on statistical analysis of experimental data combined with signal processing techniques, including low-pass filtering. It should be noted that certain studies propose methods for improving the statistical reliability of PPV predictions without significantly increasing the volume of experimental data [25].

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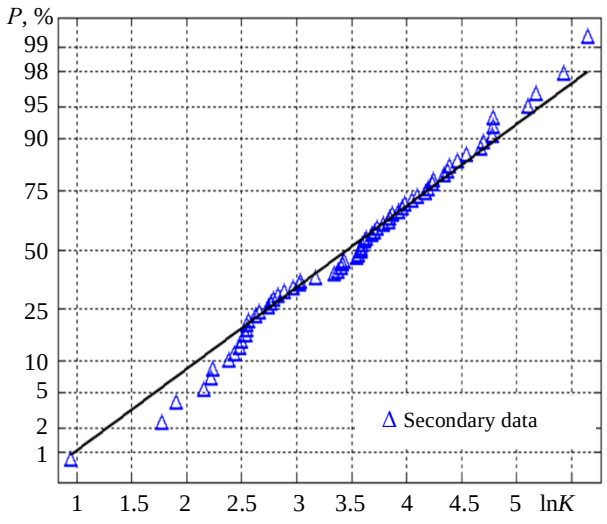


Fig.1. Cumulative natural logarithm of the seismic coefficient

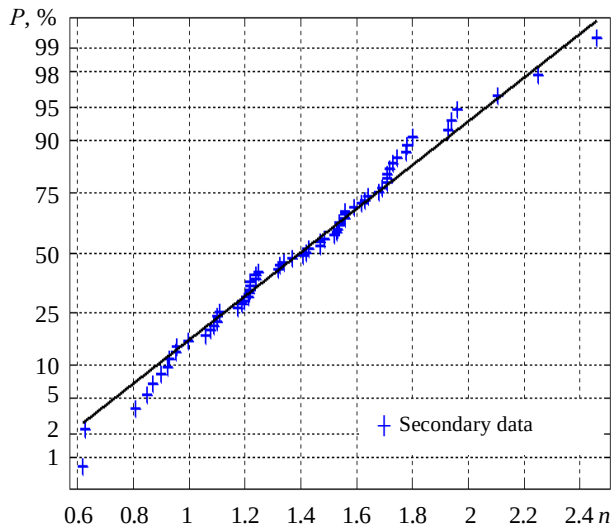


Fig.2. Cumulative straight-line graph of the attenuation exponent

Results

Based on data compiled from open sources [26, 27], a lognormal distribution of the seismic coefficient (Fig.1) and a normal distribution of the attenuation exponent (Fig.2) were obtained for the USBM formula. The distributions are limited to seismic coefficient values below 300 and attenuation exponent values below 2.5, as significant deviations from these distributions are observed at higher parameter values. Such statistical distributions for the USBM parameters are reported here for the first time.

Statistical distribution parameters for K and n at a 95 % confidence level are as follows: condition $2 < K < 300$; N is the number of data points, $N = 67$; $\overline{\ln K}$ is the mean value of the natural logarithm of the seismic coefficient, $\overline{\ln K} = 3.51^{+0.23}_{-0.23}$; σ_K is the standard deviation of the seismic coefficient, $\sigma_K = 0.95^{+0.17}_{-0.17}$; $\overline{K}$ is the mean value of the seismic coefficient, $\overline{K} = 53^{+26}_{-17}$; K_{med} is the median value of the seismic coefficient, $K_{\text{med}} = 33.5^{+8.6}_{-6.9}$; $\overline{n}$ is the mean value of the attenuation exponent, $\overline{n} = 1.40^{+0.09}_{-0.09}$.

Analysis of Fig.1 shows that noticeable deviations from the cumulative straight line occur for seismic coefficient values K below 12 for a limited number of experimental data points. In contrast, the data points for the attenuation exponent n are distributed relatively uniformly along the cumulative line and do not exhibit pronounced deviations, unlike the case when the attenuation exponent n is calculated using Sadovsky's formula. In the latter, peak values of n = 1.5 are observed, which are associated with the dominant contribution of Rayleigh waves, and values of n = 2, which are associated with body wave propagation.

To derive an expression for the classification criterion, experimental data from bulk blasting were used, as well as the methodology described in [24] and adapted for the USBM formula:

$$n = 0.33\ln K + 0.75. \quad (1)$$

It is reasonable to associate the intercept in equation (1) with the geometry of the seismic source. Therefore, from a physical standpoint, the intercept should be non-negative.

According to equation (1), the approximating function for the paired parameters K and n is expressed as:

$$n = \hat{a}\ln K + \hat{b},$$

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where $\hat{a}$ is the slope and $\hat{b}$ is the intercept.

The values of $\hat{a}$ and $\hat{b}$ are determined through statistical analysis of the paired values of *K* and *n*, whose distributions are shown in Fig.1, 2. The values of $\hat{a}$ and $\hat{b}$, along with the corresponding confidence intervals, are presented in the Table below.

Statistical analysis results

Condition	Confidence interval at a 95 % confidence level		r^2
	$\hat{a}$	$\hat{b}$	
Full sample (73 points)	0.32±0.05	0.29±0.19	0.72
Adjusted sample (68 points)	0.33±0.05	0.26±0.18	0.77

The condition for the existence of a relationship between the attenuation exponent *n* and the seismic coefficient *K*, taking into account the physical interpretation of the intercept and the lower bound of its confidence interval, is given by:

$$n \geq 0.33\ln K - 0.19. \quad (2)$$

The values of *n* that do not satisfy inequality (2) must be excluded from the dataset, together with the corresponding values of *K*, as reflected in the Table. After that, the final expression for the classification criterion is obtained:

$$n = 0.33\ln K + 0.26. \quad (3)$$

Let us evaluate the statistical significance of the paired regression equation. The calculated *F*-value is

$$F_{\text{calc}} = \frac{r^2}{1-r^2}(N-2) = \frac{0.77}{1-0.77}(68-2) \approx 221.$$

The table *F*-value at $\alpha = 0.05$ – $F_{\text{tabl}} = 3.99$, $F_{\text{calc}} >> F_{\text{tabl}}$. Hence, the hypothesis of no linear relationship between the attenuation exponent *n* and the seismic coefficient *K* is rejected.

Let us evaluate the statistical significance of $\hat{a}$, $\hat{b}$, and *r* using Student's *t*-test:

$$t_a = \frac{\hat{a}}{m_{\hat{a}}} = \frac{0.33}{0.025} = 13.2;\ t_b = \frac{\hat{b}}{m_{\hat{b}}} = \frac{0.26}{0.09} = 2.9;\ t_r = \frac{r}{\sqrt{\frac{1-r^2}{N-2}}} = \frac{0.87}{\sqrt{\frac{1-0.77}{68-2}}} = 14.9.$$

The generally accepted *t*-value (t_{tabl}) equals 2 at a significance level $\alpha = 0.05$; consequently, t_a, t_b, $t_r > t_{\text{tabl}}$. Hence, the parameters under consideration are not randomly different from zero and are statistically significant.

Equation (3) is consistent with the values of K_{med} and $\bar{n}$ and differs from equation (1) only in the value of the intercept. According to [24], data points with coordinates (*K*, *n*) located above line 2 (Fig.3) correspond to explosive sources with low seismic impact, whereas points located below line 2 (Fig.3) correspond to sources with high seismic impact. The classification of explosive seismic sources according to the USBM formula is illustrated in Fig.3. Due to the confidence interval associated with the intercept in the classification criterion, a transitional zone exists, in which the type of impact of an explosive source should be considered conditional, or which may be interpreted as the zone of sources with normal seismic impact (which would not be a critical mistake).

We can assess the relative seismic impact of different seismic sources. To do this, we need to consider two parameter pairs (*K* – *n*): (30.2 – 1.56) [28] and (177 – 1.72) from [29] (Fig.1-3). We need

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to find the difference between the attenuation exponent values in the given pairs and the values obtained according to equation (3): for pair 1, $\Delta n_1 = 1.56 - 0.33\ln 30.2 - 0.26 = 0.18$; for pair 2, $\Delta n_2 = -0.25$.

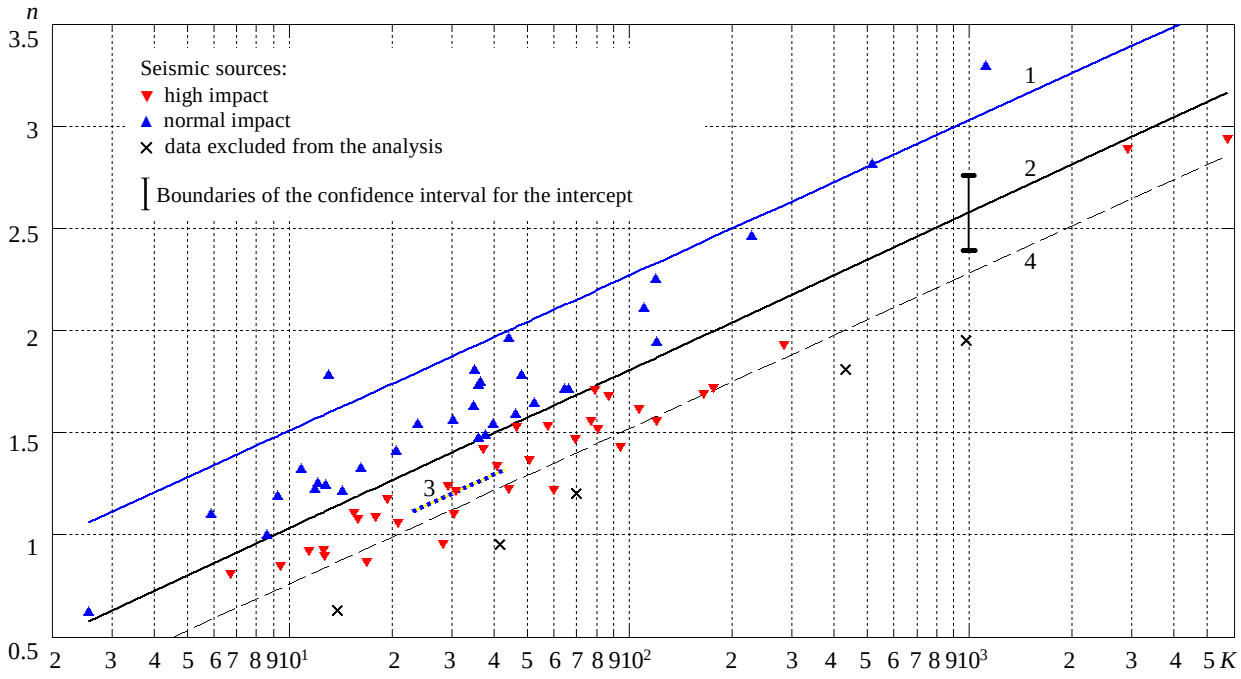


Fig.3. Classification of seismic sources according to the USBM formula

1 – the dependence of the attenuation exponent on the seismic coefficient, based on equation (1); 2 – linear regression of the sample $n = 0.33\ln K + 0.26$, equation (3); 3 – data approximation [30]; 4 – equation $n = 0.33\ln K$

Thus, pair 1 corresponds to a source with low seismic impact, whereas pair 2 corresponds to a source with high seismic impact. Since $\Delta n_1 - \Delta n_2 > 0$, the second source exhibits a higher seismic impact than the first. Conversely, from $\Delta n_1 - \Delta n_2 < 0$, the opposite is true (the seismic coefficient values were converted to cm/s based on Fig.1 in [28] and Fig.5 in [29]).

According to [31], data excluded from the statistical analysis correspond to the seismic impact of blasting in highly fractured rock masses, which is not typical of high-seismic impact sources in such rocks.

Let us compare the results obtained using Equation (3) with those obtained using a Bayesian approach and Monte Carlo simulation in [30], which analyzed 520 vibration records under various soil geology and blasting conditions in Hong Kong. Figure 3 includes an approximation of these data plotted using equation (3), but with the intercept equal to 0.08 (line 3). The dataset from [30], collected in the mid-1980s, reflects blasting practices of that period, which were characterized by higher seismic impact.

In some cases, for the same blasts, sources classified as having normal seismic impact according to Sadovsky's formula may be classified as having high seismic impact according to the USBM formula. This is observed for small charges [32]. From a physical standpoint, it is not appropriate to treat such charges as elongated sources, even over short distances.

When comparing Sadovsky's and USBM formulas for identical blasts, the key parameter is the attenuation exponent n. Physically, the attenuation exponent in Sadovsky's formula is expected to be higher than that in the USBM formulation; however, this is not always observed.

A detailed study of this issue shows that the attenuation exponent in the USBM formula exceeds that in Sadovsky's formula when experimental points are unevenly distributed over the reduced distance [33]. If the points are distributed uniformly [34], no discrepancies in the classification of seismic sources emerge. Other factors include a narrow range of measured PPV values [35], anomalously

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high values of the seismic coefficient and the attenuation exponent [36], high variability in blasting parameters [37], and low regression coefficients [38]. The inconsistency in predicting PPV values is also noted in [39], where it is reported that, at large distances, the USBM formula may overestimate PPV values compared to Sadovsky's formula. The detonation velocity along a borehole charge is finite; therefore, from the standpoint of seismic impact, a column charge may be approximated as a sequence of discrete concentrated charges.

Conclusion

A normal distribution of the attenuation exponent and a lognormal distribution of the seismic coefficient, elements of the USBM formula, was established, and their statistical characteristics were determined.

Correlation analysis of the paired attenuation exponents and seismic coefficients was performed. A classification criterion was developed that distinguishes between explosive sources with high and low seismic impact. The results of paired regression were statistically assessed, and a conclusion was made about the statistical significance of the parameters included in the classification criterion.

The challenges associated with classifying explosive seismic sources using both the USBM and Sadovsky's formulas were discussed. Examples of how the proposed classification can be applied for the relative assessment of the seismic impact of different explosive sources were examined.

Future research should focus on expanding the database of experimental measurements to identify changes in the statistical distributions of the attenuation exponent and the seismic coefficient, as well as in their paired correlations. Additional work is needed to refine the boundaries within the classification of explosive sources by their seismic impact, with the objective of optimizing blasting parameters to minimize seismic impact on protected structures while maintaining efficient rock fragmentation.

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