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Keywords

rockburst prevention, destress blasting, mining seismology, dynamic analysis

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RESEARCH ARTICLE

Predictive model of seismic vibrations' peak value induced by multi-face blasting

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Abstract

The seismicity level induced by blasting in the Polish copper mines is very important inlight of the efficiency of active rockburst prevention and safe conduct of blasting operations in the vicinity of the mining infrastructure such as shafts, workings, or function chambers (e.g., workshops, storages, etc.). Knowledge of the seismic vibrations' peak value might be the basis for designing blasting works in a way that ensures desired seismic effect. However, current experiences show that Peak Particle Velocity prediction models developed so far do not apply to multi-face blasting, where there are many vibrations' sources at the same time dotted across the mining panel. This paper presents the assumptions of a new empirical model with validation data gathered in the underground trials of group blasting. This new method allows for determining the vibration level generated by firing a single face and the value of amplitude amplification resulting from the increased number of faces fired simultaneously in the group. Preliminary analysis shows that this newly developed predictive model is characterized by a high level of reliability and therefore was applied to assess the effectiveness of blasting works in the selected panel in one of the mines belonging to KGHM Polska Miedź S.A.

Keywords: rockburst prevention, destress blasting, mining seismology, dynamic analysis

1. Introduction

Multi-face destress blasting at the moment is a principal method of active rockburst prevention utilized in Polish underground copper mines belonging to KGHM Polska Miedź S.A [1,2]. The general assumption is that an increase in the number of simultaneously detonated faces should increase the probability of tremors triggering [3]. Until recently, evaluation of the effectiveness of multi-face blasting operations was based solely on the triggering rate. Thus, if during a certain period of time after blasting, a tremor was observed in the vicinity of the detonation area, then multi-face blasting was considered effective [4,5]. Otherwise, i.e., in the absence of mining tremor, blasting operations were considered ineffective from the point of view of active rockburst prevention. Such a method was commonly used until recently, but as pointed out by Fuławka et al. [6], this approach seems to be too simplistic due to the lack of reference to the parameters describing the blasting works and the nature of the vibrations. As a result, the detonation of a single face and the detonation of dozens of faces can be considered equally effective if the mining tremor is triggered in the so-called waiting time. Obviously, such an approach is biased by the randomness of seismic events' occurrence and the lack of information about the current state of stress and strain level within the rock mass. Thus it is necessary to develop methods that will allow obtaining a broader picture of a complex process of rock mass destressing with the use of blasting.

Based on the previous authors' experience, it can be concluded that the characteristic seismic vibrations in the surrounding area of the blasting site can be used for the estimation of the effectiveness of destress blasts [7,8]. Generally, in mining engineering, the evaluation of the blasting effect is commonly performed with the use of the PPV (Peak Particle Velocity) distribution [9–17]. The efficiency of blasting may be performed by comparison of recorded

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peak particle velocity PPV_m and expected value of PPV_{calc} determined according to the formula:

$$PPV_{calc} = a \cdot (SD)^b \quad (1)$$

where: SD – is the scaled distance, a and b – are site-specific empirical constants.

Scaled distance describes the relation between the amount of explosives and the distance from the detonation point to the measuring site [18–21].

Scaled distance may be obtained with the use of the equation:

$$SD = \frac{Q^n}{r} \quad (2)$$

where: r – the distance between the firing site and measurement point; Q – maximum charge per delay, n – the site-specific empirical constant.

A detailed analysis of equations (1) and (2) allows us to clearly state that the application of these dependencies is limited to the case where the detonated charge affecting the value of PPV is accumulated in one area. In the case of multi-face blasting, the situation is quite different because there are several up to several dozen locations where the explosives are detonated at the same time (Fig. 1).

In this case, the actual value of PPV depends not only on the amount of explosives but also on the local tendency to amplify and/or attenuate the seismic wave propagating from successive faces. Moreover, explosives in a single face are detonated using an adopted firing pattern (Fig. 2).

An exemplary waveform recorded after multi-face blasting is presented in Fig. 3.

As one may notice, each subsequent delay time generates a different PPV, and in some cases, seismic waves propagating from different faces tend to amplify. Thus, it is necessary to develop a method that will allow for performing a reliable evaluation of the PPV generated by multi-face blasting.

Within this paper, the novel approach of PPV determination based on the parameters of multi-face blasting has been presented. The new method makes it possible to take into account various locations of mining faces in the analysis and determine the impact of local geological and mining conditions on the distribution of PPV values in relation to the amount of explosive used in a particular mining face. Then knowing the estimated value of PPV and comparing the results to the actual seismic records, it can be determined whether, taking into account the location of the mining faces and the amount of explosives used, blasting was effective or not.

2. Materials and methods

2.1. Geology and site description

The copper ore deposit in the considered area is classified as stratified in the sedimentary rocks (sediment-hosted copper ore deposit). Copper mineralization occurs on the border of sandstone and dolomite. The location of the copper ore deposit in space is determined by the level of the cupriferous shales. In the areas without shales, it is the direct contact zone of sandstones and dolomites. Copper ore deposit consists of the following series: sandstone, cupriferous shales, and carbonate rocks

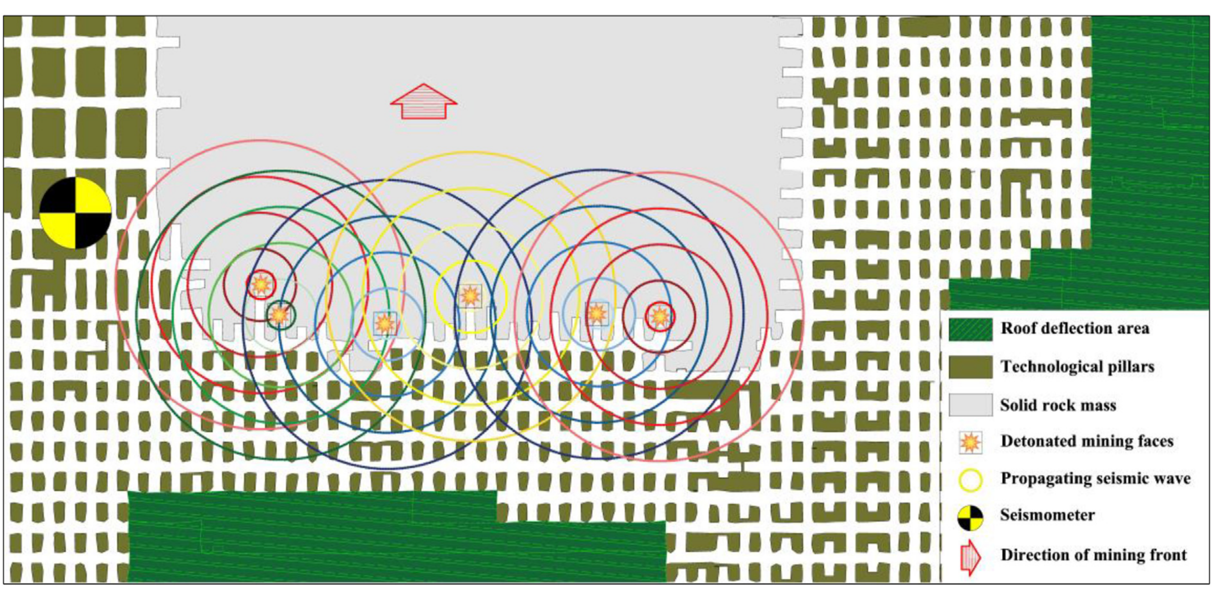

Fig. 1. Schematic representation of the propagation of seismic waves induced by multi-face blasting.

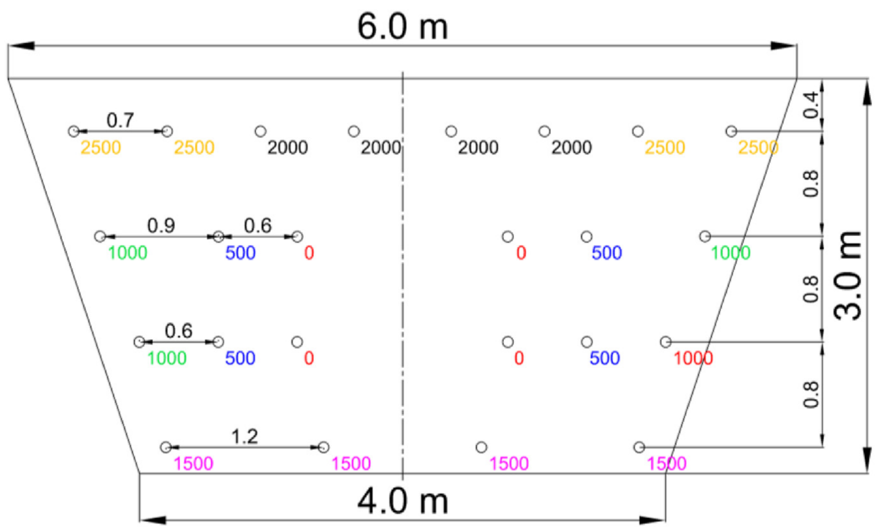

Fig. 2. Example of drilling and firing pattern with the V-cut (delay interval of 500 ms).

(dolomite). The thickness of the copper mineralized rock series varies from 1.4 m up to 2.4 m, with an average value of 1.8 m. In the analysed area deposit is located about 1100 m below the surface. The strike direction of the deposit is NW—SE with a dip angle of about 2—3° towards North-East. The direct roof is formed from dolomite with thickness varying from 13 m to 14 m. In turn, on the floor, there is sandstone with a thickness of about 300 m. At the deposit level, there are no significant tectonic dislocations in this mining area. The lithological profile with the UCS value of rock layers are shown in Fig. 4.

2.2. Characteristics of multi-face blasting operations

To ensure enough credible data set selection process took into consideration the following aspects: variable number of faces in the group, avoidance of unusual cases, and a long period of time. As a result

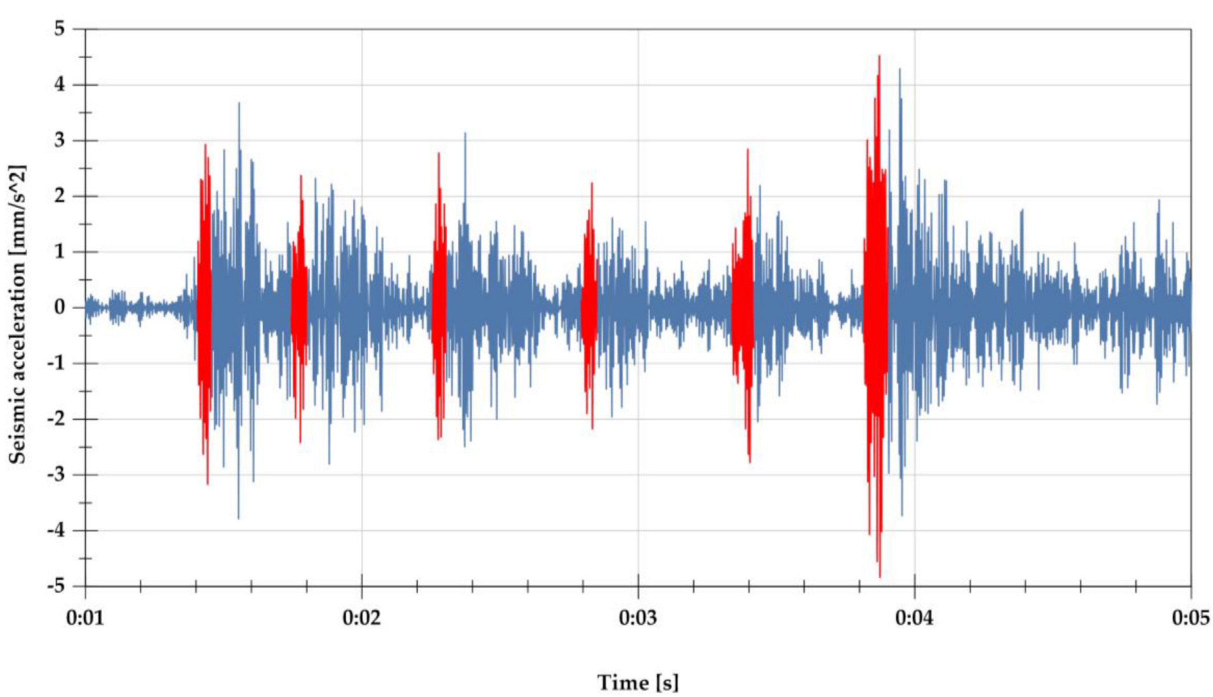

Fig. 3. Waveform representing an acceleration of seismic vibrations induced by multi-face destress blasting with the marked time of subsequent delay times (red line).

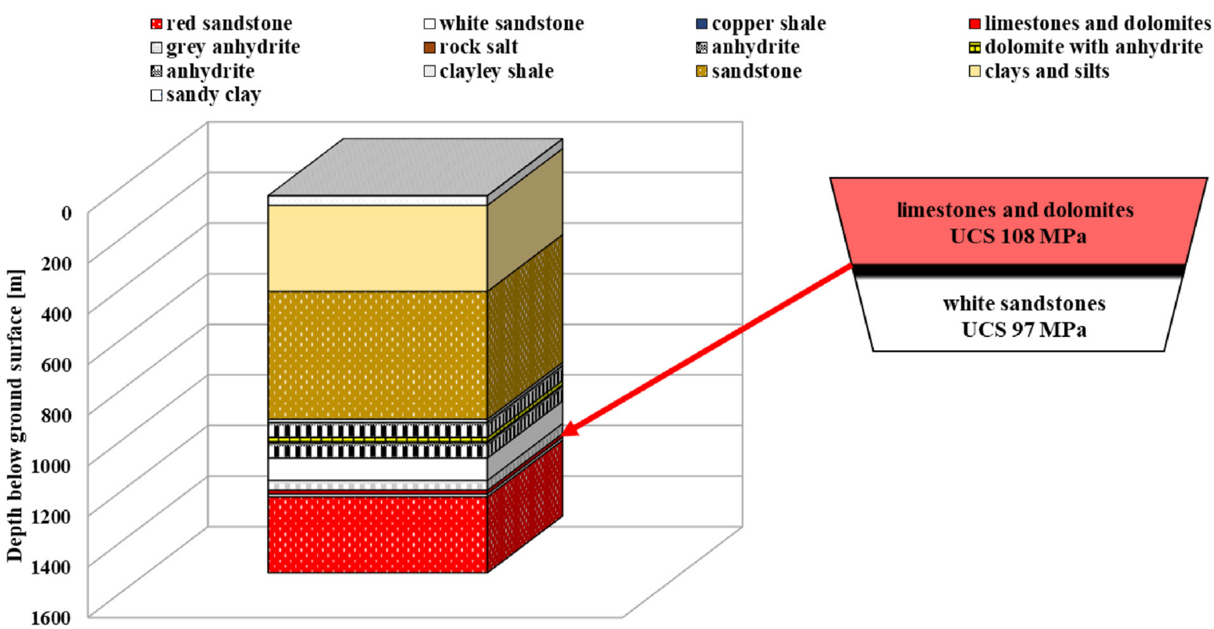

Fig. 4. Lithological profile and average UCS in roof and floor strata.

the determination of empirical *PPV* models has been performed based on records from 57 multi-face blasting conducted in chosen mining panel of Rudna mine during the period of 12 months. The number of selected blasts each month in the analysed period of time is presented in Table 1.

In the light of the seismic effect of blasting, the firing of explosives in the cut holes is the most important. In most cases, there are two types of cuts applied in KGHM mines, i.e., V-cat and parallel cut. In the parallel cuts, there are from 1 up to 3 empty holes with diameters varying from 45 mm to 89 mm and 6–8 blastholes which are loaded with explosives. Charge per delay varies from 3.5 kg to 30 kg, with an average value of 4–16 kg. V-cuts consist of 4 up to 8 blastholes with the charge per delay between 8 kg and 30 kg. No stemming is used in the standard blasting. Bulk emulsion explosives are used, which are initiated by non-electric detonators and boosters. The total amount of explosives used in group blasting in the examined mining panel during the analysed period of time varies from 300 kg to 2300 kg, while a number of simultaneously fired mining faces varied from 4 to 31. Within this 12-month-long period, the mining front advanced by about 200 m. An example of a drilling and blasting pattern is shown in Fig. 5.

Table 1. Number of selected blasts for analysis in each month in the analysed mining panel.

Month	1	2	3	4	5	6	7	8	9	10	11	12	Total
No. of blasts	3	5	4	9	4	8	4	4	4	4	4	4	57

2.3. Seismic data acquisition

Blasting operations were continuously monitored with the use of 2 seismic posts located in the vicinity of the analysed mining panel. Post no. 45 is located behind the mined-out area, while post no. 7 is located in the front of the mining front (Fig. 6). Both seismic posts are equipped with single-axis Willmore MK IIIA seismometers characterized by flat bandwidth in the range of 0.1–150 Hz. Data was collected with the use of a 32-channel recorder Elogor-C with a sampling rate of 500 Hz.

The assumption of the project is to develop a method that can be implemented immediately for use in mines using the currently existing infrastructure and monitoring devices. Therefore, for the purposes of this analysis, seismometers that are already included in the mine's seismic network were used.

Therefore author's seismometers used data from the internal mining seismological network. To analyse the characteristics of the seismic wave ahead of the front and from the side of the subfloor zones, seismometers No. 7 (in front of the mining front) and seismometer No. 45 (from the goaf side) were selected, respectively.

2.4. Determination of PPV induced by multi-face blasting

As already pointed out, equation (1) describes the predicted *PPV* value after the detonation of a single

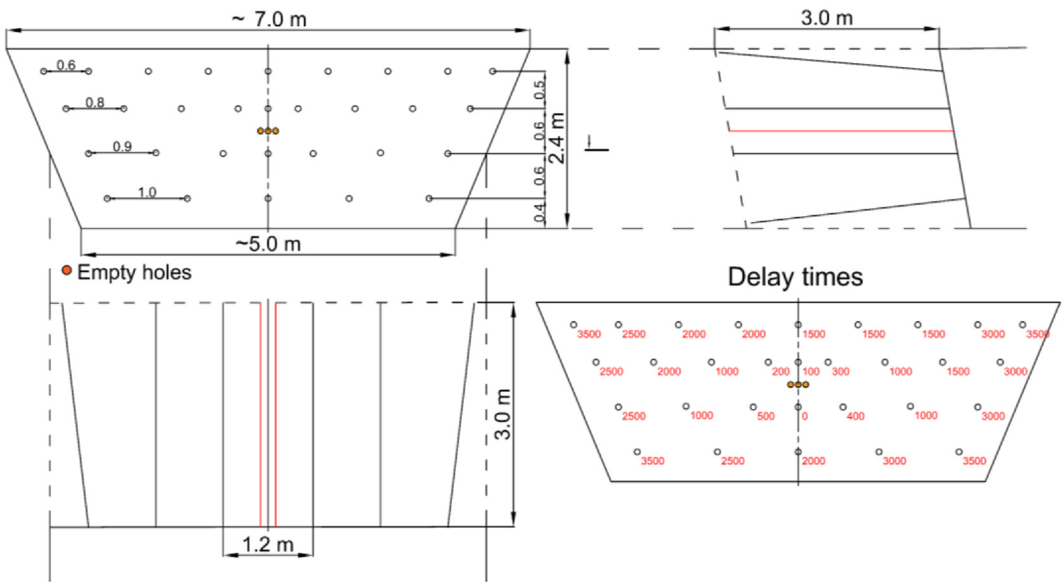

Fig. 5. An example of a drilling and blasting pattern applied in the face.

explosive charge or multiple charges located in one area and fired at the same time. However, it cannot be used to assess or predict the seismic effect of more complex blasting operations where different delays of detonators in many locations are used [22]. During the firing of explosives in a larger number of blastholes located in many faces, seismic waves may interfere with each other and, depending on local conditions, may lead to the attenuation or amplification of seismic waves.

To solve this problem, the introduction of amplification factor S to the calculation is necessary. This factor can be positive in case of amplification or negative when the signal is dumped. In this case, peak particle velocity calculation for multiple blast holes, PPV_{MH}, may be expressed as follows:

$$PPV_{MH} = PPV_{R0} + S = a \cdot (SD_{R0})^b + S = a \cdot \left(\frac{Q_{cut}{}^n}{r}\right)^b + S \tag{3}$$

where: PPV_{R0} – peak particle velocity generated by detonation of explosives in the cut holes in the nearest mining face; SD_{R0} – the scaled distance related to the detonation of cut holes in the nearest

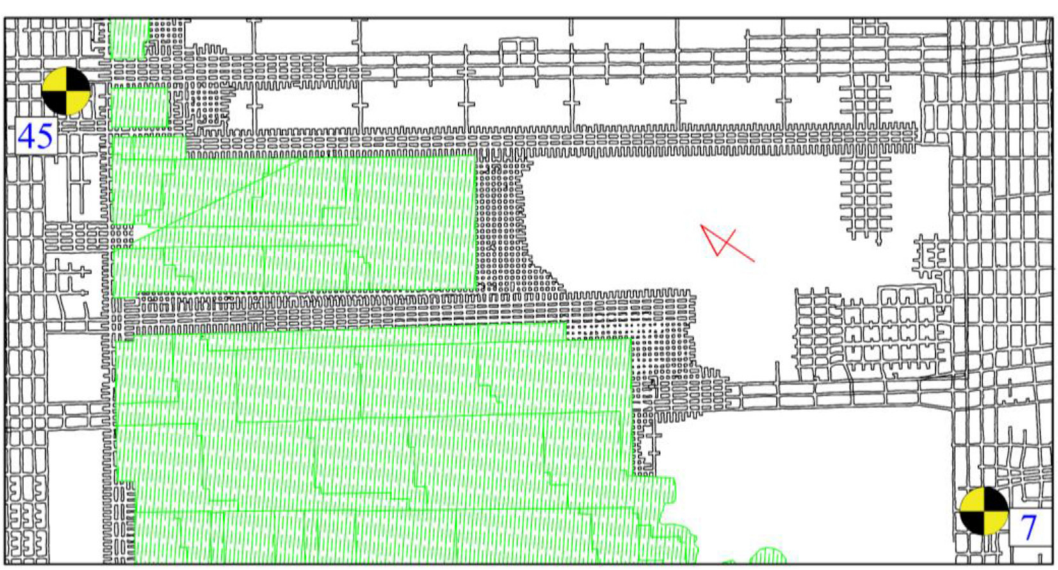

Fig. 6. Location of the seismic posts in the analysed area.

mining face; Q_{cut}– the total amount of explosives in cut holes in a single face.

The amplification factor S depends on the total amount of explosives used during multi-face blasting and local mining and geological conditions. For that reason, in the case of blasting with the same parameters, the results must be the same. According to research presented in the paper [6], the S factor in the conditions of Polish copper mines may be expressed with the formula:

$$S = \beth \cdot (Q_{total})^{\epsilon} \quad (4)$$

where: $\beth$ and ϵ are the empirical constants describing local mining and geologic conditions, and Q_{total} is the total amount of explosives.

Having PPV_{MH} as well as the records of blast-induced seismic waves, the amplitude-based effectiveness index of blasting (E_{SA}) may be performed with the use of the formula:

$$E_{SA} = \frac{PPV_{recorded}}{PPV_{MH}} \quad (5)$$

Finally, an efficiency assessment of multi-face blasting can be carried out in accordance with Table 2.

3. Results and discussion

3.1. Prediction of PPV related to the firing of the cut

Based on seismic records and parameters describing particular blasting, such as:

- amount of explosives,
- number of faces and their location,
- applied drilling and blasting pattern.

The a, b, and n parameters from formula 3 were determined. The population of results taken into analysis after the rejection of outliers was 52 for seismometer no. 7 and 55 for seismometer no. 45. Estimated values of these parameters are presented in Table 3.

Conducted analysis indicates that developed predictive models of PPV_{R0} index for examined panel well describe observed outcomes. After rejecting outliers (red points in Fig. 5), the calculated coefficient of determination R^2 and the corresponding coefficient of correlation r for both seismic posts was relatively high. Detailed values of these coefficients for each seismic post are shown in Table 4, while the graphic representation of convergence between recorded values of PPV_{cut} after the detonation of cut holes and estimated values of PPV_{R0} are presented in Fig. 7.

Table 2. Method of interpreting the effectiveness of blasting on the basis of the E_{SA} index.

E_{SA} value	Rating	Description
< 0.9	blasting ineffective	effect lower than expected
0.9–1.1	blasting moderately effective	effect close to the expectation
> 1.1	blasting effective	effect exceeds the estimated value

Table 3. Values of empirical parameters of the models.

Seismic post	The calculated empirical factor for the determination of the PPV_{R0}		
	n	a	b
ST-7	0.5	2.2893	0.2026
ST-45	0.33	3.7828	0.9360

3.2. Determination of the local value of the amplification factor (S)

Simultaneous detonation of multiple faces may contribute to the amplification of seismic waves. In general, the level of seismic enforcement is related to the total amount of explosives [6]. The local tendency to the seismic wave amplification/attenuation may be introduced to the calculation by the implementation of the S factor. The distribution of the S factor depending on the total amount of explosives used during multi-face blasting is presented in Fig. 8.

As can be seen in Fig. 8, there is a clear correlation between the local amplification factor (S) and the total amount of explosives used in group blasting in the considered mining panel. Models of local amplification factors for each seismic post are shown in Table 5.

3.3. Predictive model of PPV induced by multi-face blasting

The analysis is presented in section 3.1. and 3.2. was the basis for the determination of a predictive model of PPV induced by multi-face blasting. The model allows analysing of what level of seismic vibration may be induced by the detonation of a single mining face consisting particular amount of explosives in the cut hole and allows to predict the

Table 4. R^2 and r_s coefficient values for the prediction model of PPV_{R0}.

Seismic post	Coefficient of determination R^2	Coefficient of correlation r_s
ST-7	0.7648	0.8745
ST-45	0.8175	0.9042

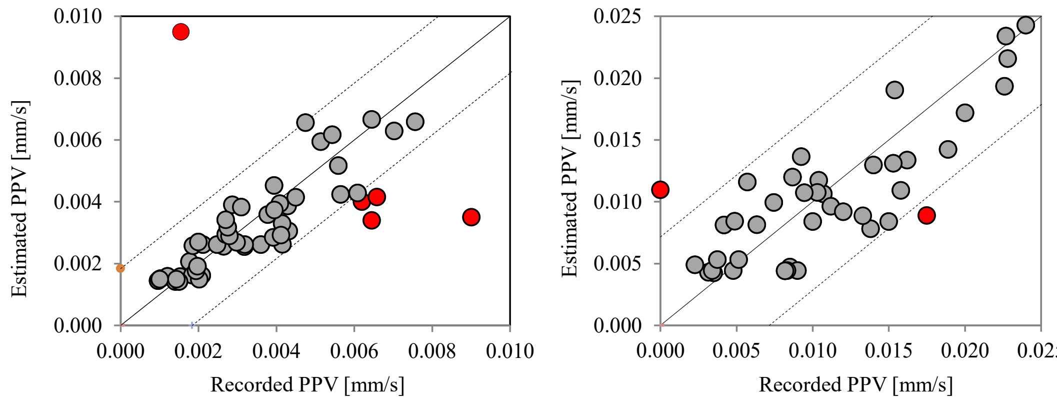

Fig. 7. Recorded PPV_{cut} values versus estimated PPV_{R0} for seismic post 7 (left) and 45 (right).

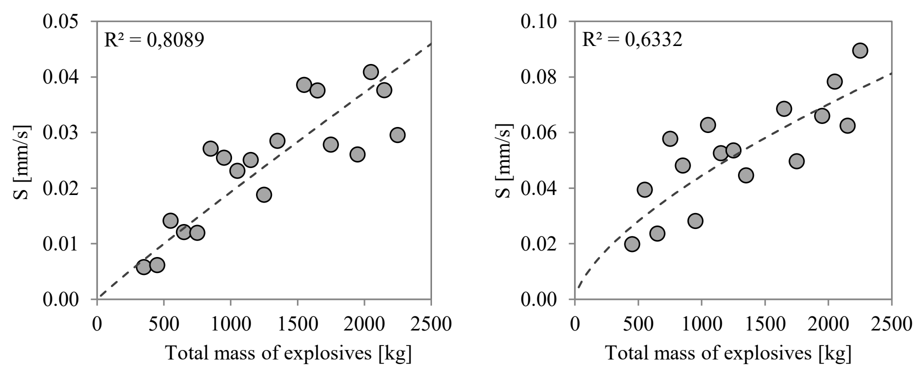

Fig. 8. Real values of the amplification factor S for posts no 7 (left) and 45 (right).

Table 5. Developed models for estimation of the local factor of the seismic amplification for seismic posts in the surrounding of the examined mining panel.

Seismic post ID	Prediction model of *S* factor	Coefficient of determination R^2	Coefficient of correlation r_s
ST-7	$S = 0.00002779 \times Q_{total}^{0.94723904}$	0.8089	0.8994
ST-45	$S = 0.00046876 \times Q_{total}^{0.65898105}$	0.6332	0.7957

seismic wave amplification with respect to the total amount of explosives used during multi-face destress blasting. The predictive models developed for examined mining panel are presented in Figs. 9 and 10.

Combining the results obtained with the use of the abovementioned models, the expected maximum velocity of seismic vibration may be assessed concerning the total amount of explosives, type of cut,

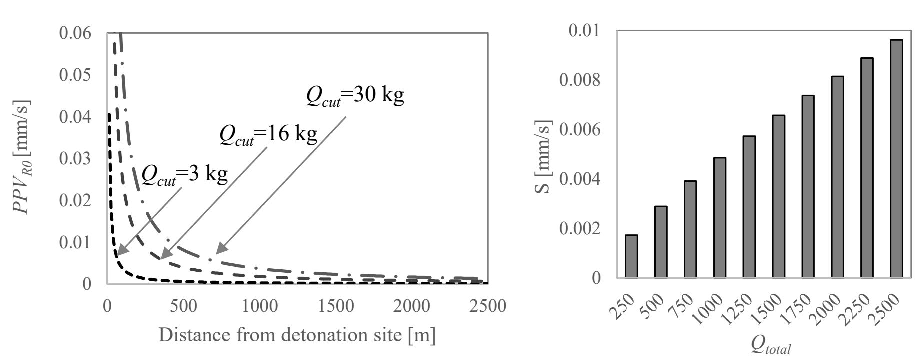

Fig. 9. Model of PPV_{R0} distribution (left) and amplification factor S (right) developed for seismic station no. 7.

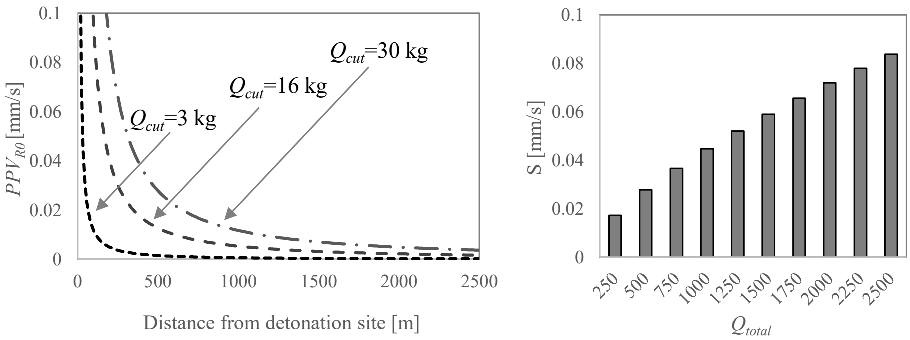

Fig. 10. Model of PPV_{R0} distribution (left) and amplification factor S (right) developed for seismic station no. 45.

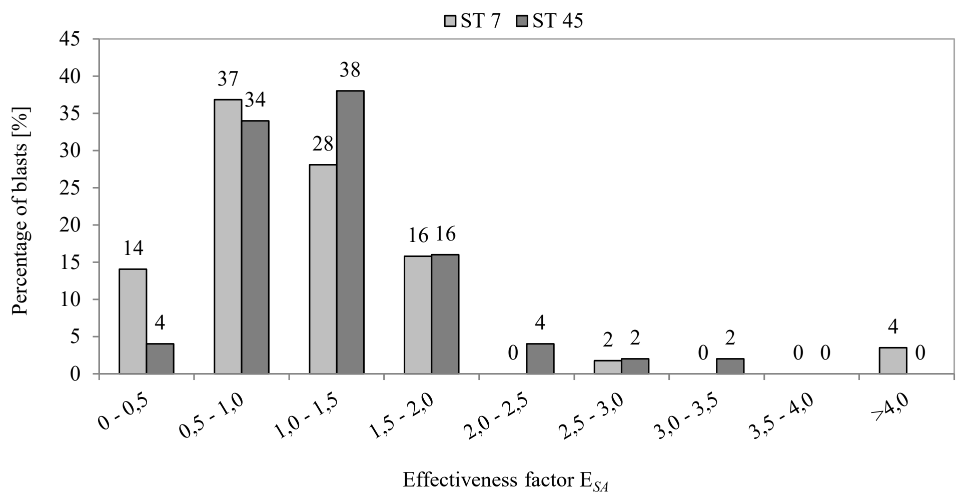

Fig. 11. Percentage distribution of group blasting in considered mining panel.

explosive charge in cut holes, and distance of mining faces from the area of interest. As can be seen in Fig. 11, the effectiveness of blasting evaluated with the use of the E_{SA} factor, carried out in the considered mining panel, varied from 0.5 up to 4.0.

When analysing the effectiveness of destress blasting in examined mining panel, it may be observed that around seismic station no. 7, over 51% of seismic waves were characterized by lower amplitude than expected, while in the case of seismic station no. 45, as many as 38% of blasts were ineffective. Such information in further steps will be base for analysis of which cases were most effective and why. This knowledge then can be used for the modification of blasting parameters.

4. Conclusions

The properly developed predictive models of *PPV* distribution are of the highest importance during the preparation of a creditable quantitative assessment of the multi-face destress blasting effectiveness. Knowing the real measured level of blast-induced seismicity and the recorded data may be compared to results obtained with the use of predictive formulas. If measured waveforms indicate the *PPV* value higher than the prediction, then it may be stated that blasting was effective. In the other case, blasting is ineffective, and some modifications in blasting patterns, location of faces, or firing times have to be implemented. Detailed insight into this process in a more comprehensive way is desirable from the rockburst prevention point of view. What is important, thanks to this method, the significance of individual parameters can be estimated for each case.

The possibility of selecting effective cases of multi-face blasting from the database will be definitely useful during the development of new, more effective ways of improving active rockburst prevention methods.

It has to be highlighted that one of the main assumptions of this work was to develop a method adapted to all multi-face blasting carried out in the mines of KGHM Polska Miedź S.A., regardless of whether one mining face or dozens were detonated simultaneously. Therefore, the mine representatives were asked to select multi-face blasting operations reflecting the full range of works carried out in a given mining panel. As a result, the above-presented analysis included blasting operations in which only a few faces were detonated, as well as cases where several dozen of faces and over 2 tons of explosives were detonated at once.

The advantage of the method presented in this article is its ease of use after selecting the appropriate parameters of the empirical formulas. Having developed the formulas for ESA and S, and knowing the parameters of blasting works in terms of the D&B pattern used, the number of faces, and the amount of explosives, it is possible to estimate the *PPV* in a few minutes concerning the parameters of the vibration source. Then, having seismic records in the vicinity of the selected site, it is possible to analyse the value of recorded vibrations and compare them to the expected value of PPV and thus determine the effectiveness of the work carried out immediately after blasting.

Ethical statement

The authors state that the research was conducted according to ethical standards.

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Conflict of interest

The authors declare no conflict of interest.

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