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Estimation of active rockburst prevention effectiveness during longwall mining under disadvantageous geological and mining conditions

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ABSTRACT

Underground longwall mining of coal seams in the Upper Silesian Coal Basin is currently being carried out under increasingly difficult geological and mining conditions. Mining depth, dislocations and mining remnants are the main factors responsible for the most significant rockburst hazard, which can be minimized via the use of active and passive rockburst prevention. Active rockburst prevention in longwalls is usually based on blasting, in order to either destress local stress concentrations in the rock mass or to fracture the thick layers of strong roof rocks to prevent or minimize the impact of high energy tremors on excavations. The accurate estimation of active rockburst prevention effectiveness is particularly important when mining under disadvantageous geological and mining conditions, which are associated with high levels of this hazard. The efficiency of blasting applied for this purpose is typically evaluated from the seismic effect, which is calculated based on seismic monitoring data and the weight of the charged explosive. This method, as used previously in the Czech Republic, was adopted in the present study to analyze conditions occurring in a Polish hard coal mine in the Upper Silesian Coal Basin. Parameters of long hole destress blastings in roof rocks (torpedo blastings) from the face of the assigned longwall in coal seam no. 507 were correct a success according to the seismic effect method and corresponded to observations made in situ. The analytical method presented enables the rapid estimation of destress blasting effectiveness and could also be useful when determining appropriate active rockburst prevention.

1. Introduction

Rockburst has long been a dangerous phenomenon for miners working in underground excavations in the Upper Silesian Coal Basin (Pelnar, 1938; Straube et al. 1972; Holecko, Ptacek, Takla, & Konecny, 1999; Budryk, 1938; Parysiewicz, 1966; Konopko, 1984; Dubiński & Konopko, 2000, Drzewiecki & Kabiesz, 2008). According to their origin and mechanism, two main types of rockburst are typically encountered:

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rockburst with its focus in the coal seam or its vicinity; and rockburst with its focus outside the coal seam, mostly in the thick layer of sandstone in the roof of the coal seam.

Rockburst hazard during the underground mining of coal seams has prompted the development of a range of rockburst prevention techniques – both passive and active – in which destress blasting plays an important role. Destress blasting is performed either directly in the coal seam or in surrounding rocks (mostly in the roof rocks). The main purpose of this blasting is to reduce stress concentrations occurring in the rock mass, although rock fracture is also important due to the associated creation of a zone in which the dissipation of tremor energy occurs. There are some other methods for the destress of rock mass and making coal seam extraction safer, for example destress drilling or hydraulic fracturing. However, colliery destress blasting in roof rocks is the main form of active rockburst prevention. The range of destress can be determined through geophysical methods, for example the seismic method. In practice it is important to get immediate information about stress drop after blasting and whether the rock mass has reached a new advantageous energy equilibrium state.

The accurate estimation of destress blasting effectiveness is of particular importance when mining under difficult geological and mining conditions, which are both correlated with seismic activity and a high probability of rockburst occurrence. Such an estimation was performed for destress blasting application in the roof rocks of coal seam no. 507, during longwall mining in one of the hard coal mines in the Polish part of the Upper Silesian Coal Basin (USCB). The depth of exploitation, mining remnants in adjacent coal seams and the presence of a thick layer of sandstone in the seam roof were the main factors responsible for the high level of rockburst hazard. To estimate the effectiveness of the blastings applied, the seismic effect method was used. This method, previously developed for use in hard coal mines in the Czech part of the USCB, was adapted to conditions occurring in one of the coal mines in the Polish section.

2. Geological and mining conditions

The mining of coal seam no. 507 with the investigated longwall lasted from January 2011 to June 2012. In the area of the longwall, seam no. 507 is deposited at a depth range from 870 to 910 m, with its thickness varying from 2.7 m to 3.8 m. The direct roof of coal seam no. 507 consists of alternating layers of shale, sandy shale and sandstone; most of these rocks possess high compressive strength (maximum 80 MPa). At a distance of more than 50 m above the seam, a thick layer (up to 60 m) of sandstone is present. The floor of coal seam no. 507 is composed of shale and sandy shale of small thickness (several meters) and is underlain by the thicker seam no. 510 (up to 8 m) (Fig. 1).

The longwall began its run from the area of the flank drift pillar. The longwall ran along the abandoned longwall goaf in the upper stage, and crossed the mine filled drift at a level of 900 m. At its end, the longwall ran in to the protecting shaft pillar and was approaching the main drift pillar. Mining edges of seams no. 501 and 502 (approximately 150 m and 135 m above seam no. 507, respectively) were presented in the longwall field. The above-mentioned difficult geological and mining conditions were reflected in the seismic activity observed.

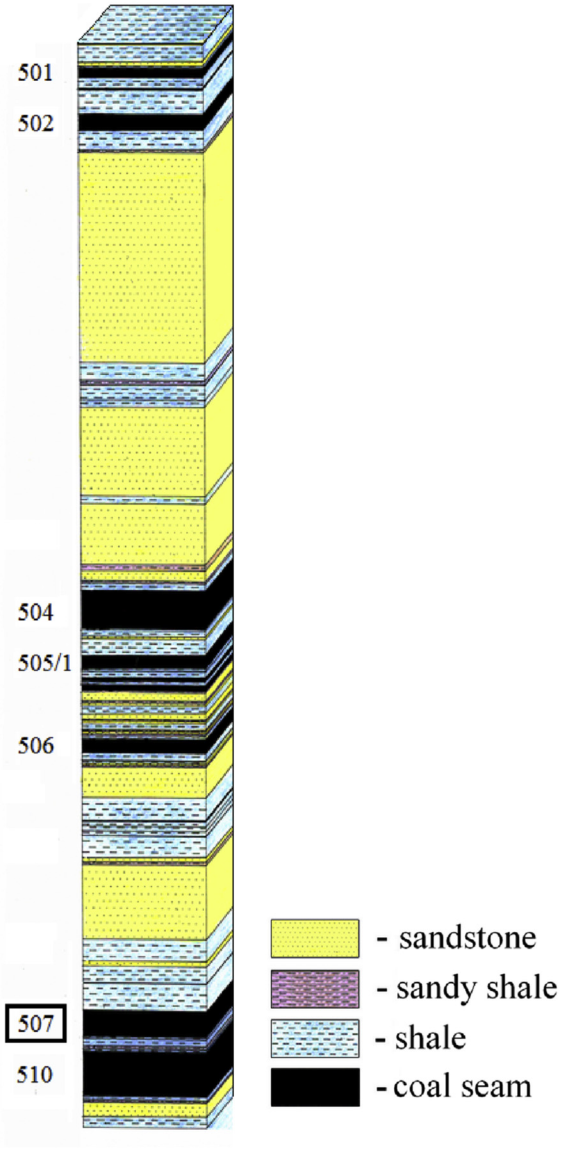

Fig. 1 – **Lithological structure of rock mass in the area of the investigated longwall.**

3. Seismic monitoring

A data set for the study site was obtained from a network of 16 seismic stations, located in underground excavations at a depth range of 320–1000 m. The network consisted of a combination of vertical-component sensors including SPI-70 seismometers and DLM-2001 geophones. The sampling rate was equal to 5000 samples per second, with the timing of the seismological system synchronized based on the Global Positioning System. Seismic stations were distributed around the investigated longwall. The error of epicenter location ranged from about 20 to 35 m, while the error of hypocenter location in extreme cases reached over 60 m, but was typically less. Errors of tremor source locations depended on the number of seismic stations whose data was used in the calculations. The configuration of the seismic network employed in the seismic monitoring of the investigated longwall in coal seam no. 507 is presented in Fig. 2, in which the squares denoted with “S” represent the seismic stations.

The intensity of seismic activity recorded in the vicinity of the investigated longwall indicated that rockburst hazard in this excavation was at a high level. The total number of recorded seismic events during the study period was 6273, with a total released tremor energy of $2.62 \cdot 10^8$ J, including 3341 events with energy in the range of 10^2 J ($0.11 \le ML < 0.63$), 1840 events with energy in the range of 10^3 J ($0.63 \le ML < 1.16$), 897 events in the range of 10^4 J ($1.16 \le ML < 1.68$), 160 events in the range of 10^5 J ($1.68 \le ML < 2.21$), 34 events in the range of 10^6 J ($2.21 \le ML < 2.74$) and one tremor of $2 \cdot 10^7$ J ($ML = 2.9$). Locations of high-energy tremor sources generated during the longwall mining of coal seam no. 507 are presented in Fig. 3, in which the small circles denote tremors of energy 10^5 J, average-size circles represent tremors of 10^6 J and the biggest circle representing a tremor of $2 \cdot 10^7$ J. Fig. 3 also depicts monthly longwall advance (from I 2011 to VI 2012).

During the period from August 2011 to March 2012, the level of rockburst hazard in the longwall was at its highest level, with about 70% of the seismic events with energy in the range of 10^5 J, 97% of seismic events with energy in the range of 10^6 J and the strongest tremor with an energy of $2 \cdot 10^7$ J all taking place. At this time the longwall ran beneath mining edges in upper seams no. 501 and 502 (generally parallel to the longwall) and was approaching the edge of the shaft pillar. Mining of coal seam no. 501, responsible for the creation of the mining edge in the area of the longwall took place between thirty and forty years ago. Coal seam no. 502 was mined in the area of the longwall in the 1970s and 1990s. Induced tremors occurred in the front of the longwall face (average horizontal distance from the longwall face of 90 m). At the foci of the strongest tremors the shear component predominated, this is probably connected to the fracturing of the thick layer of sandstone located above coal seam no. 507 (Wojtecki & Dzik, 2013). Because of this high level of seismic activity and the associated intensity of rockburst hazard during longwall advance, active rockburst prevention was applied.

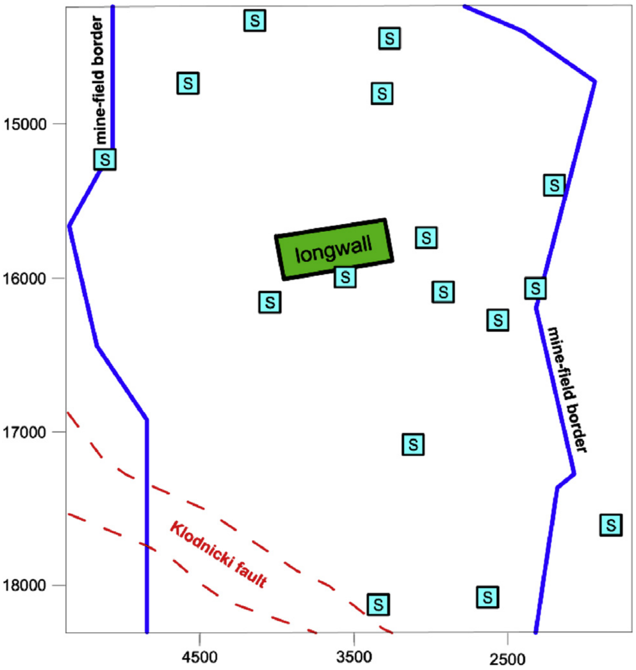

Fig. 2 – Configuration of the seismic network in the area of the investigated longwall in coal seam no. 507.

4. Active rockburst prevention in the investigated longwall

Active rockburst prevention took place, largely, in the form of destress blastings in roof rocks. The main purpose of these blastings was to destress the rock mass ahead of the advancement of the longwall face. Blastholes were drilled with the use of a hydraulic drilling machine. Two drilling machines were transported to the longwall. The deviation angle and inclination angle were determined with the use of a protractor. During drilling an outflow of drilling fluid containing borings was observed, so the type of rock was recognized. The pneumatic loading of blastholes was always applied. Emulinit PM explosive material was used for each blasting, with a heat energy equal to 2278 kJ kg^{-1} (data according to the material producer, Nitroerg: http://www.nitroerg.pl/pl/produkty/emulinit-pm.html).

For each destress blasting stage, six blastholes with a length of 40 m (arranged in pairs: one pair in the middle of the longwall, and the others placed 60 m from longwall headings) were drilled. The blastholes were deviated from the longwall face to the north-east and south-east at an angle of about 40°, and were inclined upwards at an angle of 35°. Explosive material occupied around 15 m of each blasthole, with the rest filled with stemming. During each destress blasting stage, 432 kg of Emulinit PM was detonated. According to the parameters presented, eleven destress blasting stages were performed, directly provoking immediate tremors with a seismic energy range of $3 \cdot 10^4$ J to $9 \cdot 10^4$ J. These blastings were performed at, on average, 25 m intervals along the longwall advance.

Due to the aforementioned increase in rockburst hazard level that appeared in August 2011, the destress blasting stages were subsequently performed using a larger amount of explosives. From this point onwards, 96 kg of Emulinit PM was loaded in each blasthole, which had a length of almost 20 m (Fig. 4). During each destress blasting stage, 576 kg of explosives was detonated. In addition, blasthole inclination was increased to 40°, an arrangement which was considered to be optimal based on both site geological structure and technical capability (Fig. 4). The column of explosives was located in the roof of coal seam no. 507, in the layers of sandstone, which is deposited alternately to layers of insufficiently solid rocks (mainly shale). The first layer of sandstone is deposited about 3.2–9.5 m above coal seam no. 507. The second layer is deposited about 21.8–23.1 m above coal seam no. 507. At the end of October 2011, the location of blasthole pairs in the investigated longwall was modified appropriately according to the occurrence of spontaneous high-energy tremors. During

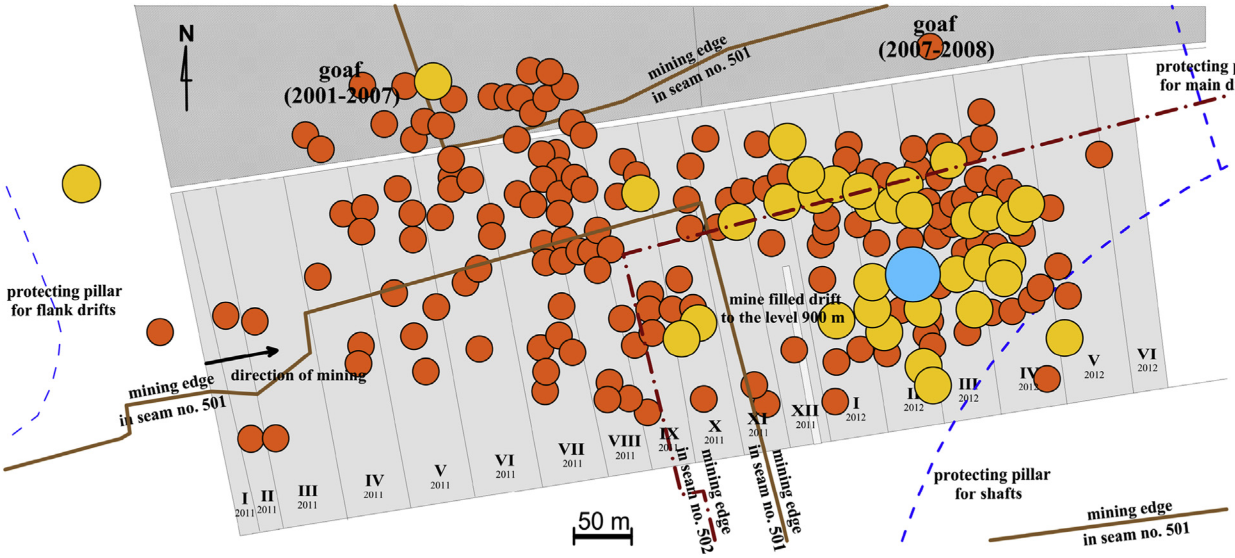

Fig. 3 – Location of high-energy tremor sources induced during longwall mining of coal seam no. 507.

the period of increased seismic activity lasting until the end of January 2012, thirteen destress blastings with the described parameters were performed. These blasting stages, which provoked immediate tremors with an energy range from $4 \cdot 10^4$ J to $9 \cdot 10^4$ J, were performed on average at 15 m intervals along the longwall advance.

From February 2012 onwards, a stable distribution of blasthole pairs in the longwall was restored. A decrease in seismic activity and associated rockburst hazard led to a reduction in the frequency of destress blastings within the longwall (at an average longwall advance interval of 23 m). Nine torpedo blastings were performed, provoking immediate tremors with an energy range from $4 \cdot 10^4$ J to $8 \cdot 10^4$ J. The location of blastholes drilled from the longwall face during longwall advance and the epicenters of the provoked tremors are presented in Fig. 5.

Via the use of the seismic effect method, the estimation of the effectiveness of the destress blasting of roof rock was then performed.

5. Evaluation of destress blasting effectiveness in surrounding rocks

An evaluation of the effectiveness of the destress blastings was carried out in line with methodology established in the Czech part of the USCB by Knotek et al. (1985) and subsequently verified by Konicek, Soucek, Stas, and Singh (2013). This methodology is based on Seismic Effect (*SE*) calculations and their evaluation which takes into consideration the success of destress blasting with regards to stress release. *SE* is typically defined as the ratio of seismic energy released in the rock mass when blasting, to the considered energy of the particular detonated charge (more details can be found in Konicek et al. 2013) and can be calculated according to the following formula:

$$SE = \frac{E_{ICM}}{K_{ICM} Q} \tag{5.1}$$

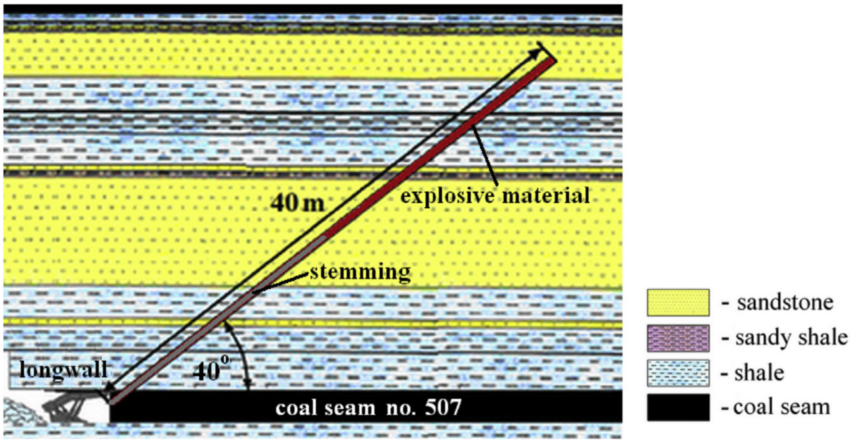

Fig. 4 – Destress blasting from the longwall face – a side view.

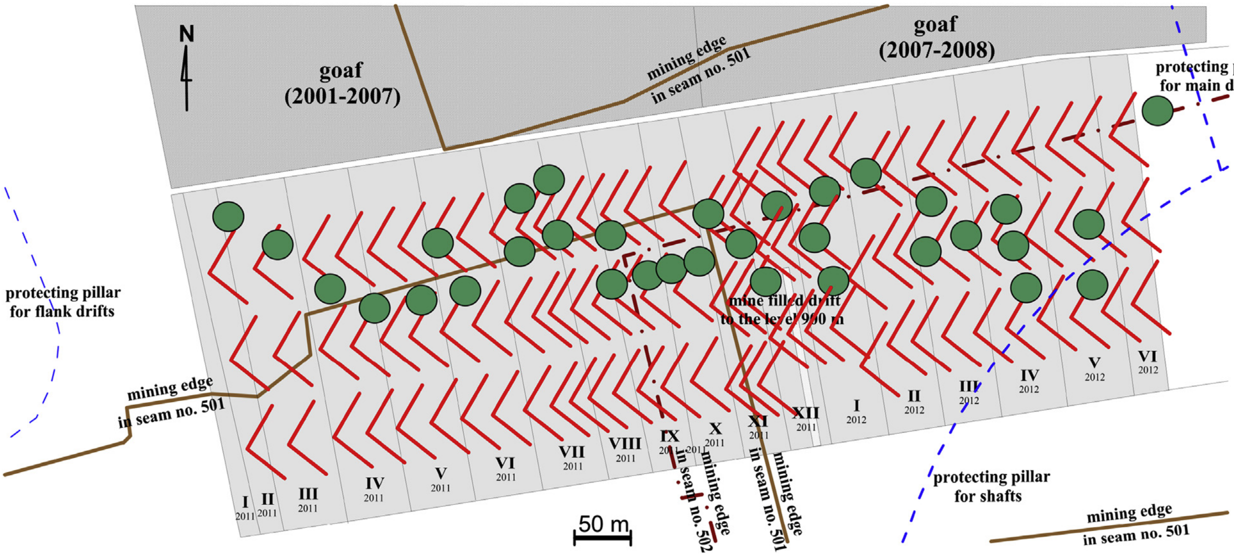

Fig. 5 – Location of blastholes drilled from the longwall face and the epicenters of provoked tremors during the mining of coal seam no. 507 (from I 2011 to VI 2012).

where E_{ICM} is seismic energy in J in the investigated coal mine; Q is the weight of the explosive charge in kg; and K_{ICM} is the coefficient of the natural and mining conditions of the rock mass in the coal mine in question. Coefficient K_{ICM} must be determined for the conditions in which seismic monitoring is carried out; the seismic energy of the registered events is calculated in the same way. Here coefficient K_{ICM} was determined based on the conditions recorded in the Polish colliery according to the method detailed in Konicek et al. (2013).

The previously mentioned relationship was validated through the field study of the seismic energy registered during the underground destress blasting of roof rocks (torpedo blastings). Coefficient K_{ICM} was determined via statistical data analysis of this seismic energy and the weight of the explosive charge from in situ monitoring of nine longwalls, for which active rockburst prevention was performed across a wide range (256 destress blasting stages in roof rocks). As the applied methodology (Knotek et al., 1985; Konicek et al., 2013) is based on linear regression, it must be proven that the data is derived from a normal distribution. The statistical analysis employed included exploratory analysis aimed at determining data distribution characteristic, error elimination, correlation analysis for the confirmation of the dependence between variables, as well as dispersion analysis. Logarithmic transformation (i.e. ln E_{ICM}) was used for the seismic energy, with origin values (i.e. Q) employed for the weight of the explosive charge according to exploratory analysis.

Based on this analytical procedure, a linear dependence between the transformed seismic energy data (ln E_{ICM}) and the non transformed weight of explosive charge data (Q) was identified, as represented by the regression line $\ln E_{ICM} = 9.7925 + 0.0022Q$ (Fig. 6).

The standard deviation of the transformed seismic energy in the above relationship is 0.633. Data located under the straight line parallel to the regression line and shifted by the standard deviation of the transformed seismic energy was then selected, as depicted in Fig. 6, with the median value of this new data set used to determine the coefficient $K_{ICM} = 59.23\ \mathrm{J} \times \mathrm{kg}^{-1}$.

The classification system developed in order to evaluate Seismic Effect values, based on criteria obtained from data distribution probabilities and according to Equation (5.1), is presented in Table 1.

The value of the coefficient K_{ICM} was used to establish the classification system for the evaluation of *SE*. This classification was made according to the distribution of the data probability from calculated seismic effects according to equation (1). Quartiles and the level of outlier occurrence were used for the creation of boundaries (1.4; 2.3; 3.5; 5.9 respectively in Table 1). The first boundary (1.4) is the first quartile, the second boundary (2.3) is the second quartile (median), the third boundary (3.5) is the third quartile and the last boundary (5.9) is the level of outlier occurrence.

The value of the coefficient K_{ICM} was used for this classification. According to this approach, if the *SE* of destress

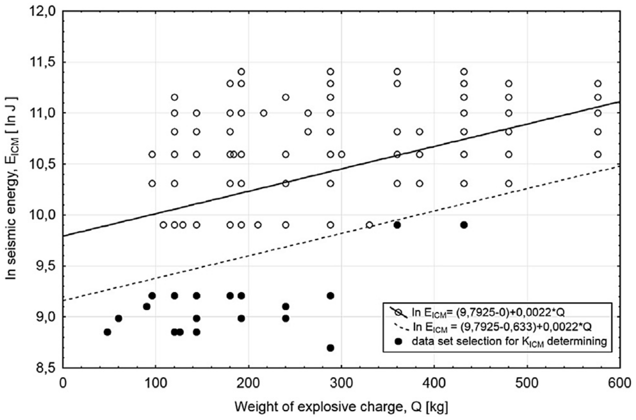

Fig. 6 – Transformed seismic energy as a function of weight of charge, according to conditions occurring in the investigated coal mine.

Table 1 – Classification system for the evaluation of SE.

Seismic effect (SE)	Evaluation of seismic effect	Percentage of data set
$SE < 1.4$	insignificant	20.7
$1.4 \leq SE < 2.3$	good	29.1
$2.3 \leq SE < 3.5$	very good	25.1
$3.5 \leq SE < 5.9$	extremely good	19.5
$SE \geq 5.9$	excellent	5.6

Table 2 – Parameters of destress blasting of roof rocks performed from the longwall face.

Date	Q [kg]	E_{ICM} [J]	SE [J·kg-1]	Evaluation of SE
2011-02-14	432	3.00E + 04	1.2	insignificant
2011-03-21	432	9.00E + 04	3.5	extremely good
2011-04-04	432	5.00E + 04	2.0	good
2011-04-18	432	4.00E + 04	1.6	good
2011-05-02	432	5.00E + 04	2.0	good
2011-05-16	432	5.00E + 04	2.0	good
2011-05-30	432	6.00E + 04	2.3	very good
2011-06-13	432	5.00E + 04	2.0	good
2011-06-27	432	3.00E + 04	1.2	insignificant
2011-07-11	432	4.00E + 04	1.6	good
2011-07-18	432	7.00E + 04	2.7	very good
2011-08-01	432	4.00E + 04	1.6	good
2011-08-21	576	4.00E + 04	1.2	insignificant
2011-09-04	576	5.00E + 04	1.5	good
2011-09-19	576	4.00E + 04	1.2	insignificant
2011-10-10	576	8.00E + 04	2.3	very good
2011-11-28	576	8.00E + 04	2.3	very good
2011-12-11	576	9.00E + 04	2.6	very good
2011-12-26	576	7.00E + 04	2.1	good
2012-01-08	576	7.00E + 04	2.1	good
2012-01-22	576	6.00E + 04	1.8	good
2012-02-13	576	6.00E + 04	1.8	good
2012-02-27	576	8.00E + 04	2.3	very good
2012-03-12	576	6.00E + 04	1.8	good
2012-03-26	576	4.00E + 04	1.2	insignificant
2012-04-09	576	7.00E + 04	2.1	good
2012-04-22	576	8.00E + 04	2.3	very good
2012-05-06	576	8.00E + 04	2.3	very good
2012-05-20	576	7.00E + 04	2.1	good
2012-06-03	576	6.00E + 04	1.8	good

blasting in roof rocks is equal to 1.4, the blasting releases only 1.4 times more energy than the energy of the explosive. If the energy released by destress blasting is less than 1.4 times the explosive energy, the destress blasting effect is insignificant from a stress release point of view. Similarly, when the *SE* of the destress blasting is equal to 5.9, 5.9 times more energy than the energy from the explosive is released. In this latter case, the destress blasting effect can be considered excellent from a stress release point of view. Although seismic energy is fundamental to the stress release effect and the *SE* calculations, it represents only a small proportion of the total blasting energy, with a considerable amount of the seismic energy observed in rock mass stress release. It should be noted that an evaluation of destress blasting effectiveness according to *SE* calculation alone represents an evaluation of only one main goal of destress blasting, that goal being stress release.

6. Results and discussion

During the mining of coal seam no. 507, a total of 33 blastings were conducted from the longwall face, three of which were performed together with blasting in the coal seam (60 kg of explosives detonated in 12 blastholes). For each of the remaining 30 self-contained blastings, the seismic effect *SE* was calculated, with the effectiveness of each blasting then estimated on the basis of these values (Table 2).

Among the 30 tremors induced by destress blastings, the seismic effect varied from insignificant to extremely good, with 58% being good and approximately 24% very good. One blasting produced an extremely good effect, while around 15% of blastings were insignificant. In general, the designed active rockburst prevention procedure – torpedo blastings in roof rocks from the longwall face – can be considered to be appropriate based on the obtained seismic effect values. In most cases, the destress blastings impacted on stress field in the area ahead of the longwall face. Calculated seismic effects and their evaluation indicate that most of the destress blastings provoked geomechanical processes correlated with stress release. Recorded after destress blastings, tremors were mostly of a higher energy which would to be due to the detonation of the explosives. Destress blastings in roof rocks mostly brings a new and advantageous state of stress equilibrium ahead of a longwall face.

7. Conclusions

The systematic planning and designing of destress blasting in roof rocks enabled longwall mining to be carried out safely at a site subject to a high level of rockburst hazard. The estimation of destress blasting effectiveness is particularly important when mining under disadvantageous geological and mining conditions, both of which influence rockburst hazard occurrence. An estimation of destress blasting effectiveness can be made via the use of the seismic effect method. This method can be adapted to local conditions (geology, mining system, blasting parameters, seismic network parameters etc.) occurring in any concrete coal mine.

Here the seismic effect method was applied for the estimation of the effectiveness of long-hole destress blasting of roof rocks (torpedo blastings) performed in coal seam no. 507 in a coal mine in the Polish part of the USCB. In light of the seismic effect method, the effectiveness of destress blasting was in most cases at least good. The present findings correlate with observations made in situ, with none of the high-energy seismic events having any destructive effects in the openings. The mining of coal seam no. 507 via the longwall investigated was completed successfully, despite difficult geological and mining conditions.

The presented evaluation of stress release via destress blasting based using *SE* calculation is the first such study to test these methods on conditions occurring in the Polish hard coal mining industry. With the use of the presented method, destress blasting effectiveness can be estimated in a simple and rapid manner, thus enabling modifications to the blasting procedure to be made if required. Further investigations should be carried out under different geological and mining conditions and blasting parameters.

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