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Research paper

The effect of selected rockburst prevention measures on seismic activity – Case study from the Rudna copper mine

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ABSTRACT

In order to face threats from mining tremors a number of organizational and technical prevention methods are applied in underground mines. Unfortunately, most of these methods are based on the experience of crew and there is uncertainty whether in practice all of the executed operations are suitable and necessary in the given conditions. Analysis were performed for one of the mining districts of the Rudna copper mine, Poland. In this paper, selected methods of rockburst prevention in the G-4/8 district are described and the recorded seismicity is analysed. On the basis of the data provided by the personnel of the mine, maps of mining progress were generated. This permitted the mined out areas as well as backfilled excavations to be calculated as a function of time. The results were presented in quarterly periods. Furthermore, the seismicity recorded was correlated with the rate of mining progress, the rate of mined out zones and the active rockburst prevention effectiveness. Finally, it was concluded that correlation between the opening area and energy of seismic events may be observed under the mining panel conditions considered. A similar conclusion applied as regards the quarterly speed of mining and the frequency of event occurrence.

1. Introduction

Seismic hazard in KGHM copper mines has been observed since exploitation began. The continuous increase in mining depth and mining near tectonic faults causes the occurrence of a greater number of high energy tremors (Guha, 2000, pp. 159–215; Li, Cai, & Cai, 2007; Zorychta & Burtan, 2012). Progress of the mining work may be associated with sudden rock mass energy release, and can be the cause of the dynamic destruction of mine workings (Drzewiecki, 2017).

To minimize the negative effects caused by increased seismic activity, a number of preventive and forecasting actions were carried out. Generally, these treatments were related to rockburst control techniques and can be divided into technological (long-term), active (instant) and organizational methods (Fig. 1), whereas their selection is usually based on the designers' experience.

It is well known that the most effective approach to rockburst prevention is utilizing a group of instant methods, consisting of provoking tremors by the detonation of an explosive charge in blast holes.

However, experience gained from previous exploitation leads to the conclusion that the seismicity level depends on the progress of workings in a particular mining panel and the geological and mining conditions at the site.

Taking the above into account, a question arises: have the exploitation system, the geometry of mining field and the rockburst prevention methods been chosen appropriately? The economic aspects lead to the operation being planned in a way that achieves maximum extraction with minimal costs. As a result, rockburst prevention may not always be a priority at the design stage (Goszcz, 2004). Therefore it is worth looking into the methods of long-term prevention and correlating them with the recorded seismic activity. This will allow a decision to be made concerning which treatments have a real impact on reducing seismicity within a considered mining panel. Some of the prevention methods are only descriptive (e.g. organizational methods or clean mining without leaving rests), thus it is almost impossible to quantify them and then correlate them directly with the registered seismic activity in order to determine their effectiveness. Nevertheless, many preventive procedures are at least partially measurable, such as sequence, the direction of mining (Pytel, Świtoń, & Wójcik, 2016) or exploitation

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METHODS OF ROCKBURST CONTROL		
LONG-TERM	**INSTANT**	**ORGANIZATIONAL**
SEQUENECE AND DIRECTION OF MINING	GROUP PRODUCTION BLASTING	PERSONNEL TRAINING
MINE WORKINGS GEOMETRY	PRODUCTION/ RELIEVE BLASTING IN SOLID AHEAD	ORGANIZATION OF ROCK MECHANICS SERVICE
APPLIED ROOF CONTROL METHODS	FLOOR RELIEVE BLASTING	HAZARD ANALYSES
GROUND SUPPORT	ROOF RELIEVE BLASTING	ZONES OF HIGH RISK DESIGNATION
CLEAN MINING WITHOUT THE RESTS	ROOF STRATA HYDRO-FRACTURING	AWAITING PERIODS
ABANDONMENT OF MINING	WATERING OF ROCK MASS	PERSONNEL REDUCTION

Fig. 1. Methods of rockburst control in KGHM mines (Butra & Kudełko, 2011).

progress. So it is possible to combine these with the registered seismic activity (Butra, 2010). Therefore the main objective of this paper is to assess the effect of selected rockburst prevention methods on seismicity in mines using the example of the G-4/8 mining panel in the Rudna mine. For purpose of the analysis and further calculations, the data of all recorded tremors since January 2008 was used. It includes the frequency of occurrence, energy and location of each seismic event.

2. Materials and methods

2.1. Geological and mining characteristics of G-4/8 mining district

The G-4/8 mining parcel is located in the eastern part of the Rudna copper ore mine, in the immediate vicinity of Żelazny Most tailings pond's safety pillar. The deposit in this area is classified as a sediment-hosted type of copper deposit. It contains the Rotliegend grey sandstone and copper-bearing shales of early Zechstein. Estimated copper ore sediment thickness varies from 0.6 m to 2.2 m. The deposit is extended in the NW-SE direction and declines about 3° in the NE. The immediate roof strata contains clay dolomite with a thickness between 0.2 m and 0.4 m. Above the layer of clay dolomites, dark grey dolomite which has an approximately thickness of about 2.5 m and grey coloured lime dolomite with a thickness of about 0.1–0.6 m are present. The total thickness of the carbonate rock stratum varies from 35 m to 50 m. The floor strata contain quartz sandstones with a thickness between 13 m and 17 m and Rotliegend red-quartz sandstones with an approximate thickness of 300 m. The layers of dolomite within the G-4/8 mining panel includes different kinds of inclined and vertical cracks filled with anhydrite, clay or gypsum, usually targeted toward the NW-SE and NE-SW directions. The room-and-pillar mining method with roof deflection was used in the mining panel analysed. Until June 2010, the mining operations were carried out towards the SW direction. Thereafter, due to difficult mining and geological conditions, the direction of mining was shifted to NW (Fig. 2).

2.2. Analysis of the observed seismic activity which occurred within the G-4/8 mining panel

Continuous development of mining works within the Rudna mine led to the necessity of installing a seismic monitoring system, which includes several dozen seismometers and accelerometers located on the surface and underground. The location of seismic monitoring devices is presented in Fig. 3. The measurements were carried out using both single and multi-axial geophysical devices (Grzebyk, Jaśkiewicz-Proć, & Stolecki, 2017; Koziarz, Wróbel, Anderko, & Mirek, 2015). Each mining tremor generates individual waveforms which are analysed to determine the time, location, and magnitude of a single event (Leake, Conrad, Westman, Afrouz, & Molka, 2017).

Seismic activity observed within the G-4/8 mining district between 2008 and 2014 was characterized by high variability. The greatest total energy emitted from the rock mass took place in 2012 and achieved a total energy per year of $E_s = 2.38 \cdot 10^8$ J. Only 10% of the recorded seismic events were classified as high-energy tremors, i.e. events with energy greater than 10^5 J (Table 1).

Within the framework of the analysis only tremors with energy greater than 10^3 J were considered. Events of lower energy were excluded, assuming their negligible impact on mining safety. The distribution of emitted energy in reference to the number of events is presented in Fig. 4.

The total quarterly emitted energy of tremors increased evenly over time between the 1st quarter of 2008 and the 4th quarter of 2010. At the beginning of 2011, the amount of total released energy started to fluctuate significantly. However, the highest emitted energy value was observed in the first quarter of 2012, when 1.6×10^8 J of energy was released from the rock mass. In the subsequent quarters, there were also major fluctuations in energy values associated with events and in general the energy values remained at a high level. Furthermore, the number of events in different quarters fluctuated significantly during the considered period.

2.3. Correlation between the applied rockburst prevention methods and the observed seismic activity

To evaluate the effectiveness of the applied rockburst prevention methods, it is necessary to correlate the progress of the mining works with the observed seismic activity. This may enable the determination of whether a particular method brings the desired effect. The term of opening size is defined in the project of exploitation within the given mining parcel. The opening size of the G-4/8 panel should include four to seven rooms or about fifty to one

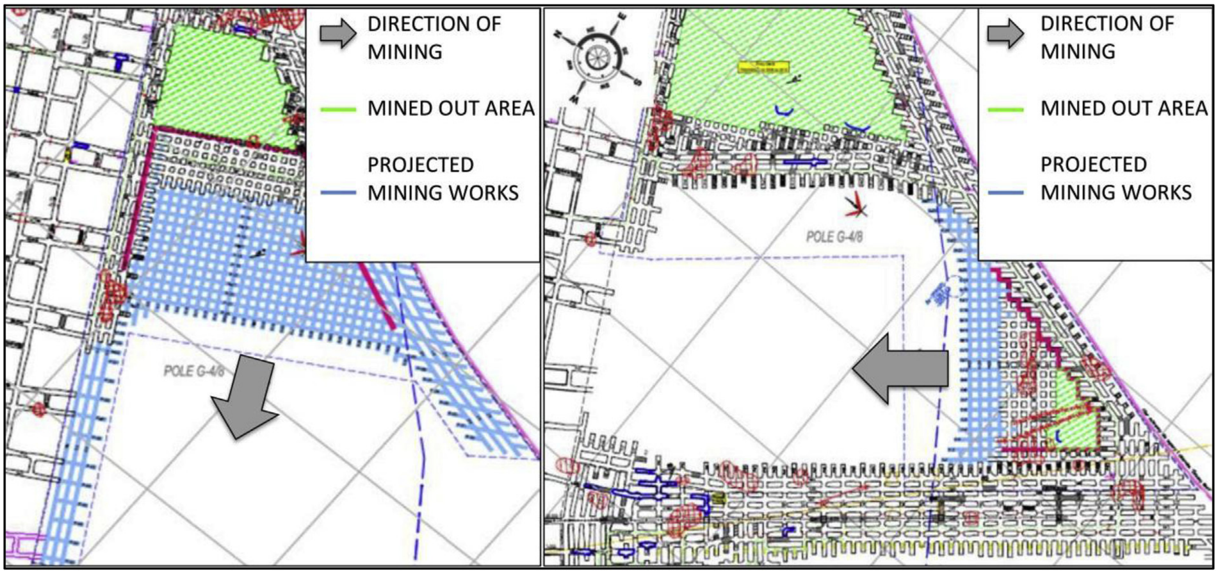

Fig. 2. Direction and progress of mining before June 2010 (left) and after the shifting of mining direction (right) (KGHM., 2011).

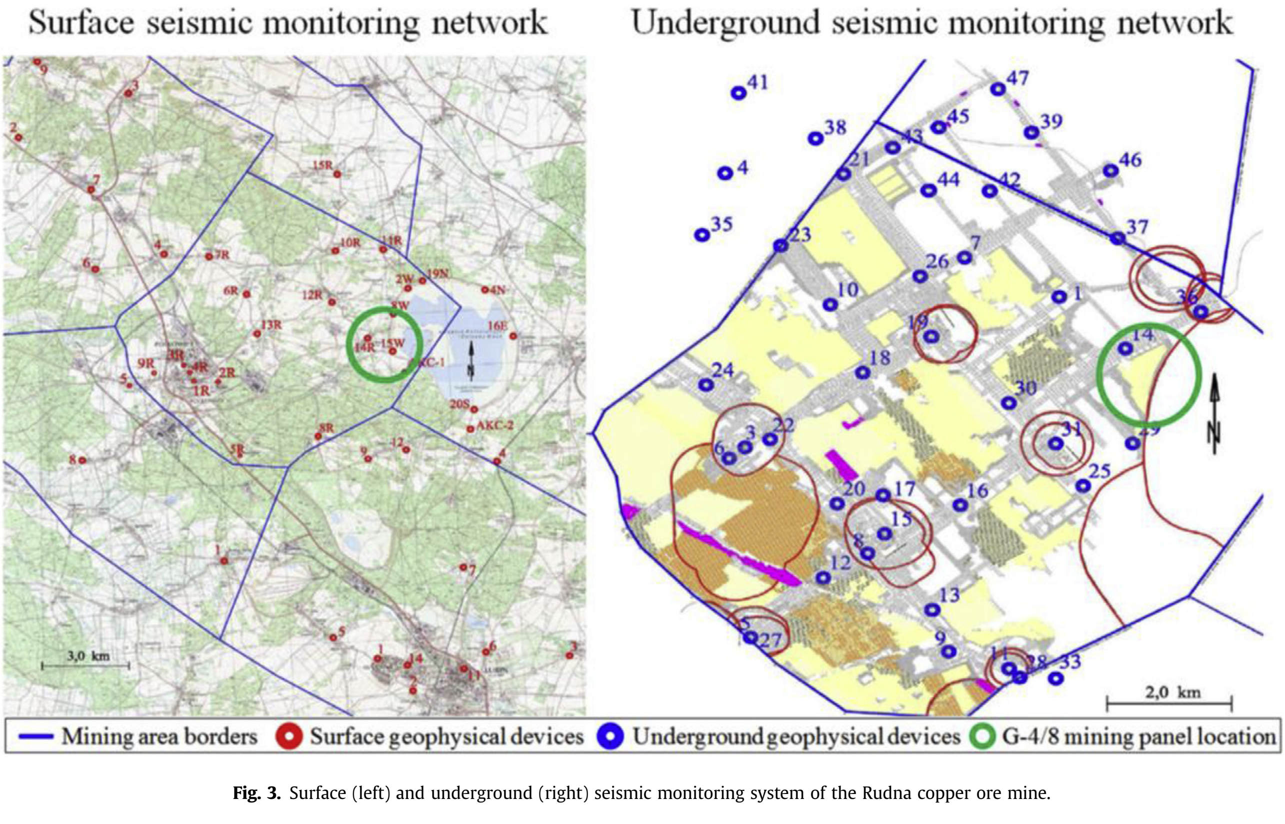

Fig. 3. Surface (left) and underground (right) seismic monitoring system of the Rudna copper ore mine.

hundred meters. Theoretically, through knowing the length of the front and opening size (Fig. 5), it is possible to calculate the actual opening area according to the following formula:

$$O_A = \frac{O_s \cdot L_f}{10\,000} \quad [\mathrm{ha}] \tag{1}$$

where:

O_A – opening area, ha,
O_s – opening size, m,
L_f – front length, m.

However, in the case of asymmetry mine workings (Fig. 6), due to difficulties in mining and geological conditions, the size of the opening area may change during mining progress. Therefore, it is crucial to define what the speed of mining means. Is it concerned with the progress of mining only or does it describes all of the works related to the development of mining and the mined out area? Thus, both situations were considered in further analysis. Material excavated from the rock mass and technological pillars is transported to a discharge point, so it is difficult to define the

Table 1
Number of tremors in different energy classes recorded between July 2008 and September 2014.

Year	Low energy tremors		Number of events in different energy classes ($E_s < 10^2$)							Number of tremors with energy greater than 10^3 J	Total emitted energy [J]
			10^3	10^4	10^5	10^6	10^7	10^8	10^9		
2008	17	3	2	15	5	1	0	0	0	23	$6.89 \cdot 10^6$
2009	27	1	5	12	16	4	0	0	0	37	$1.56 \cdot 10^7$
2010	36	2	5	17	24	5	0	0	0	51	$2.55 \cdot 10^7$
2011	102	5	4	4	8	6	1	0	0	23	$4.60 \cdot 10^7$
2012	285	17	23	16	4	5	4	0	0	52	$2.38 \cdot 10^8$
2013	81	4	6	13	2	1	0	0	0	22	$8.22 \cdot 10^6$
2014	31	2	1	6	0	1	0	0	0	8	$2.74 \cdot 10^6$

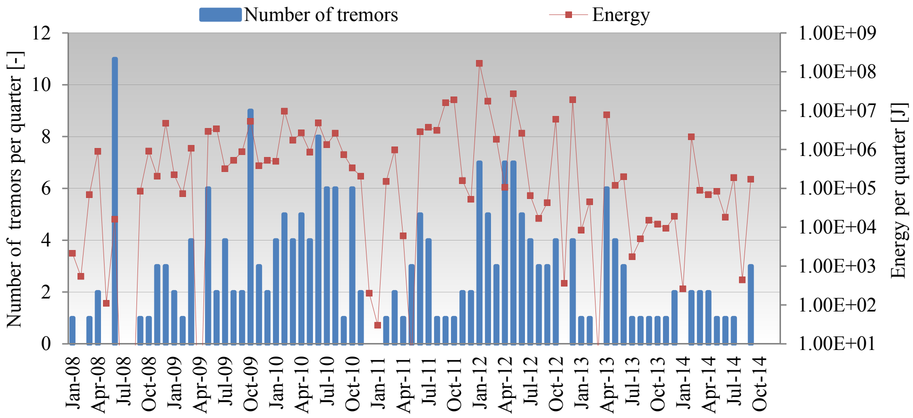

Fig. 4. Seismic activity within the G-4/8 mining parcel between 2008 and 2014.

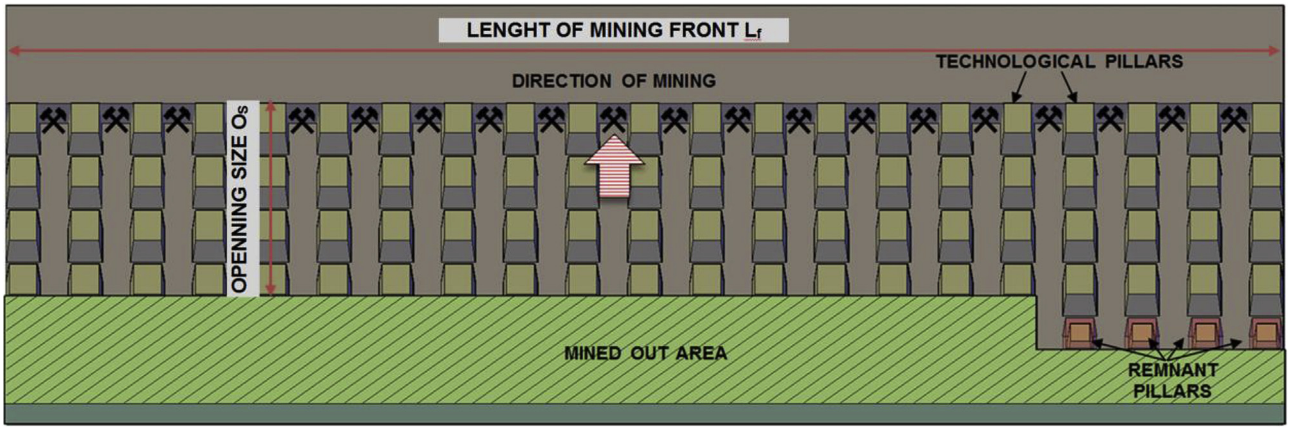

Fig. 5. Example of the mining method used in KGHM copper mines.

weight of rock coming from the mining front and from the remnant pillars. Therefore, in the case of workings with a similar height, a more precise description of the progress of mining works should be based on the area (in hectares), as in this paper. Fig. 6 shows the contours of the progress of mining works (the advance of the mining front and the progress of the mined out zone), which was used to calculate the progress of mining and the opening area at specified periods of time.

The progress of exploitation is defined by the mined out areas (in hectares) per quarter (Fig. 6 – left). Based on the cloud of points, respectively, representing the amount of the total emitted energy and the number of tremors, with respect to the excavation progress, trend lines were generated and the Pearson correlation coefficient was calculated according to the following formula:

$$r_{xy} = \frac{\sum(X_i - \overline{X}) \cdot (Y_i - \overline{Y})}{\sqrt{\sum(X_i - \overline{X})^2 \cdot \sum(Y_i - \overline{Y})^2}} = \frac{\frac{1}{n}\sum X_i Y_i - \overline{XY}}{\sigma_X \cdot \sigma_Y}\ [-] \qquad (2)$$

where:

X_i – i-value of X population,
$\overline{X}$ – average of X population,
Y_i – i-value of Y population,
$\overline{Y}$ – average of Y population,
σ_X – standard deviation of X,
σ_Y – standard deviation of Y.

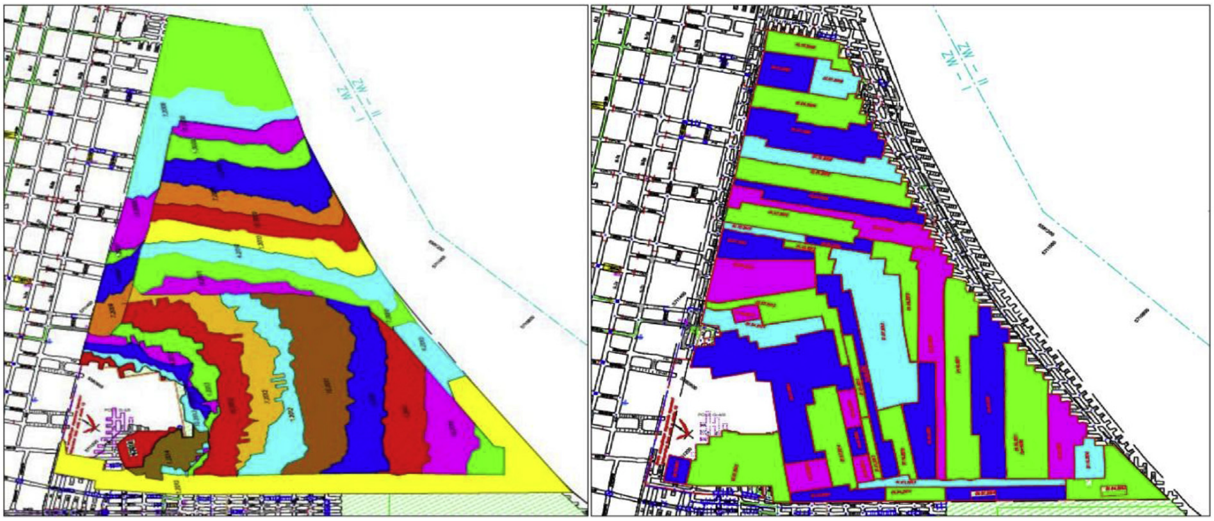

Fig. 6. Contours of progress of the mining front advance (left) and progress of mined out zones (right).

3. Results

3.1. Determination of the relationship between the progress of mining and the observed seismic activity

The relationship between the progress of mining and associated seismic activity is shown in Fig. 7.

Matching the energy-related model with the quarterly mining face advance shows a correlation value of $r_{xy} = 0.18$, which means there is a lack of a linear relationship. When comparing the number of events with the progress of mining, a much better correlation is observed, i.e. $r_{xy} = 0.34$. This means that a correlation between the number of tremors and mining front advance is moderate positive. It should also be noted that the coefficient of the correlation is highly sensitive to outliers. This means that a weak correlation can be caused by one energy peak; in this case, the stress relief event which was recorded in first quarter of 2012 (seismic energy greater than $1.8 \cdot 10^8$ J) should be treated as an outlier. In order to limit the impact of the abovementioned tremor, an analysis of annual changes was carried out (Fig. 8).

When comparing the mining face advance to the total emitted energy, the coefficient of the correlation increased to 0.21 which means a weak uphill relationship. On the other hand, the correlation between the number of tremors and face advance increased to 0.80. That in turn shows a very strong positive relationship from the perspective of the number of tremors. It is clear that better correlation is caused by a reduction in the impact of outliers through the averaging of quarterly values. However, it is still difficult to assess which time window fits best for this type of analysis.

Fig. 9 shows a similar trend in the quarterly mining progress and quarterly energy emitted from the rock mass. The quarters in which the speed of mining increased were characterized by higher levels of energy emitted from the rock mass. The relationship between the opening area and the total energy of the tremors is presented in Fig. 8, while Fig. 9 shows the correlation between the number of tremors (of each energy class), the advance of the mining front per quarter as well as the change of frequency on a tremor's occurrence from particular energy classes in respect to quarterly excavation progress.

Based on Fig. 10 one may conclude that with an increase in the opening area there is a slight upward trend in tremors from each energy class. Particular attention must be paid to the increase in high-energy tremor occurrence when the quarterly rate of excavation threshold of 3.5 ha/quarter has been exceeded. This may suggest that higher seismic activity can be caused by some thresholds of maximum mining face advance per quarter in specific mining and geological conditions being exceeded.

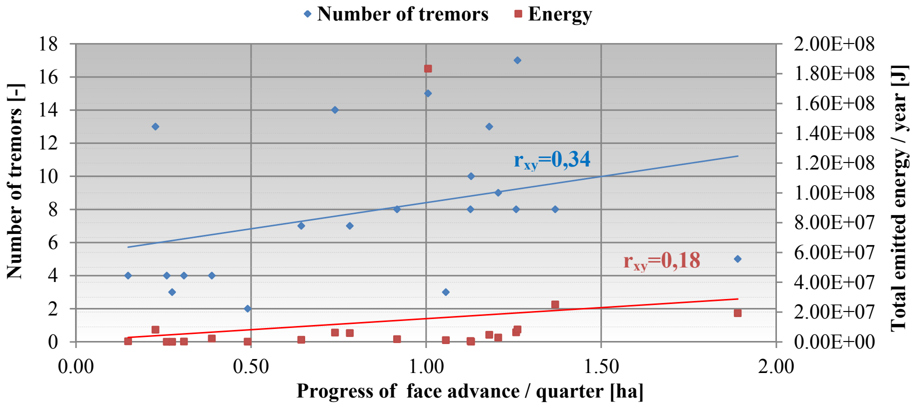

Fig. 7. The relationship between the mining face advance and energy, as well as the number of tremors in the quarter.

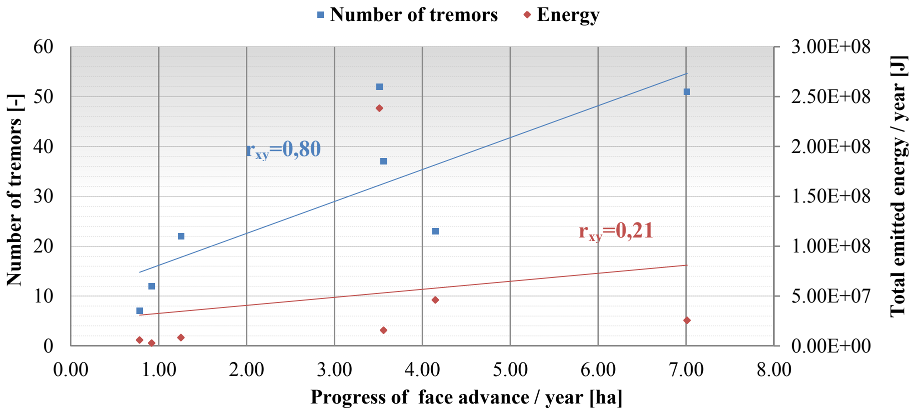

Fig. 8. The relationship between the mining face advance and energy as well as the number of tremors in the annual cycles.

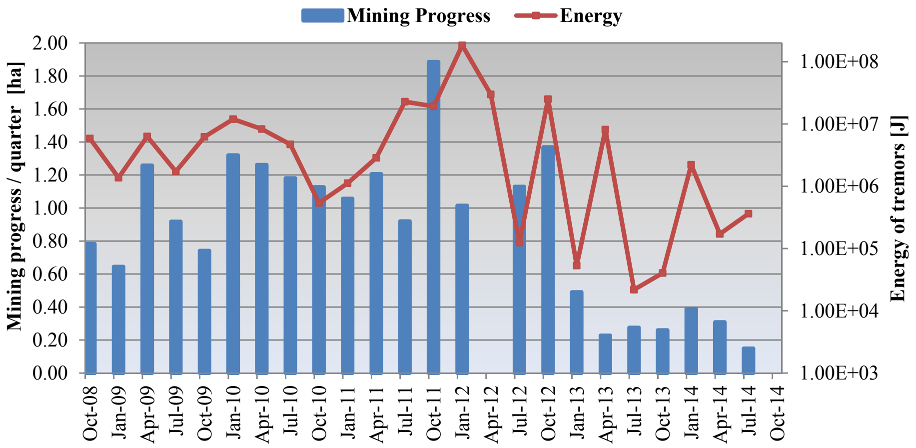

Fig. 9. The relationship between the size of the excavated area and energy as well as the number of tremors per quarter.

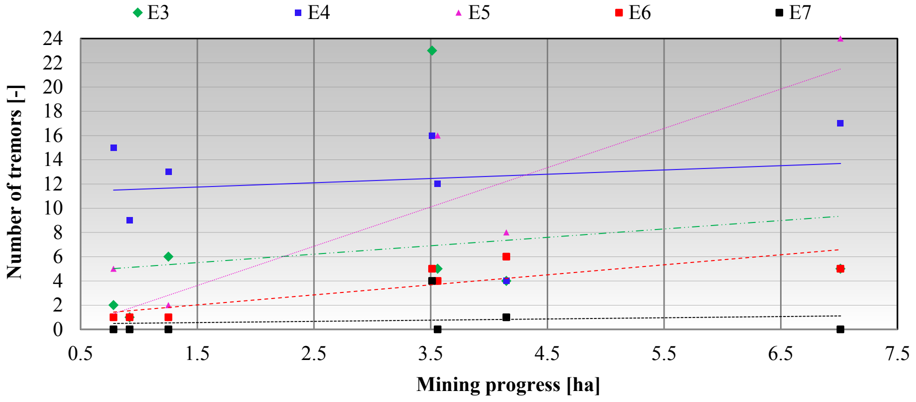

Fig. 10. Number of tremors of each energy class related to mining progress.

3.2. *The impact of the opening area on seismic activity*

The correlation procedure of the opening area with seismicity was similar to the procedure presented in section 3.1. The only difference was that the opening area was determined by subtracting the mined out zone from the total excavated area for each quarter. The results of the analyses are shown in Figs. 11–13.

Therefore, it can be concluded that the coefficient of the correlation between the opening area and the total emitted energy reached 0.26 (a weak positive relationship) in the quarterly period analysis and 0.35 (a moderate positive relationship) in the case of the annual time window. Comparison of the opening area with the number of tremors shows that the coefficient of the correlation reaches a value of 0.12 (no or negligible relationship) in quarterly analysis and 0.79 (a strong positive relationship) in annual analysis.

Based on Figs. 11 and 12 one may conclude that the coefficient of the determination rises with the increasing duration of the analysed time periods. It is worth noting that both the quantity and

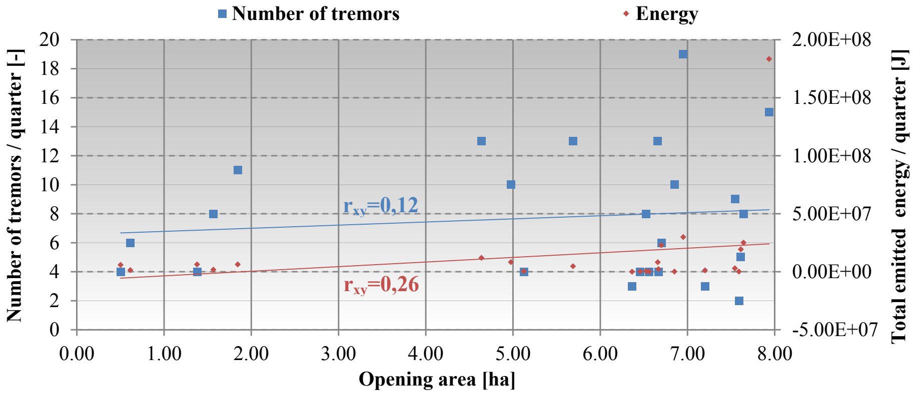

Fig. 11. The relationship between the opening area and the energy as well as number of tremors in a quarterly cycle.

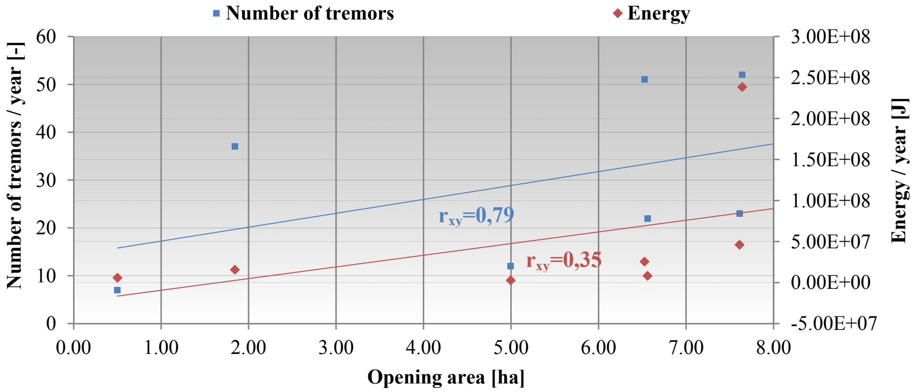

Fig. 12. The relationship between the opening area and the energy as well as number of tremors in an annual period.

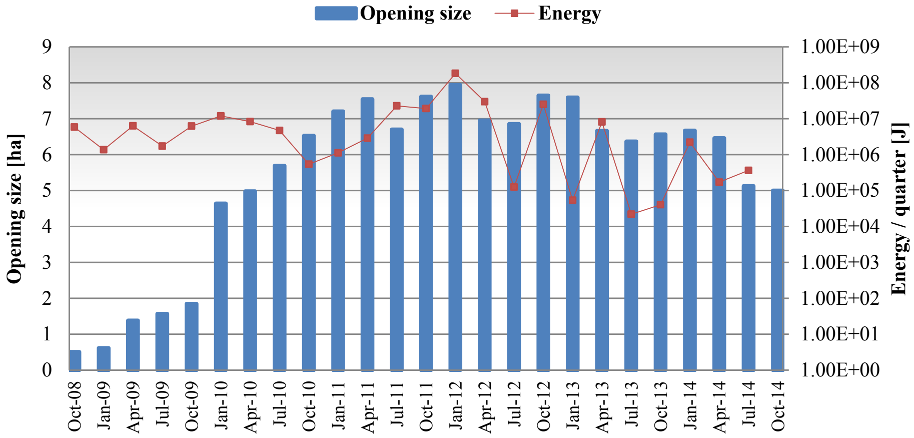

Fig. 13. The relationship between the energy of events and the opening area.

energy of events accumulate when the mined-out area exceeds 6 ha. The size of the opening area was rising until January 2012, when the maximum quarterly energy was released from the rock mass (Fig. 13). Moreover, the progress of the mined out zones was associated with a significant decline in seismic activity within the G-4/8 mining panel.

On the basis of Fig. 14 it was also found that the occurrence of tremors with respect to the opening area varied depending on their energy class. An overall increase in the number of tremors depends mainly on events from the E3 J energy class. Tremors assigned to higher energy classes, i.e. E4 J and E5 J, revealed a downward trend. An increase in the total emitted energy was determined due to the tremors from E6 J and E7 J energy classes which showed an upward trend.

3.3. *Effectiveness of blasting in mining tremor inducement*

The extraction of flat copper ore deposits in Polish deep copper mines is performed primarily by the use of blasting technology, which is also one of the most effective approaches of rockburst prevention and is applied as group winning blasting, strain release blasting in rock-mass, and blasting in the roof/floor strata and

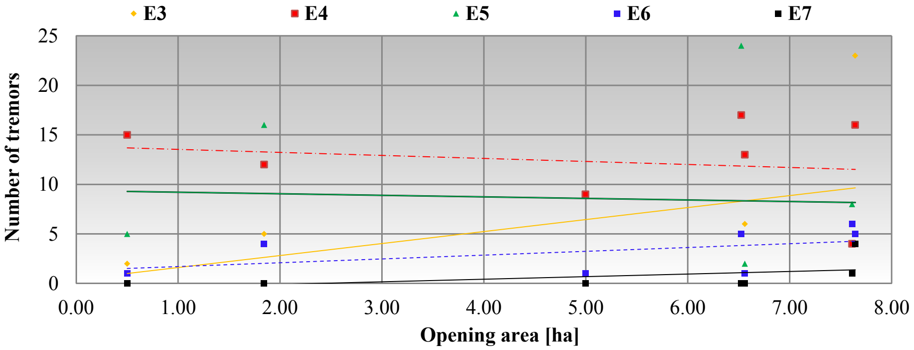

Fig. 14. Number of events of the particular energy classes in relation to the opening area.

pillars if they are able to accumulate a high amount of strain energy. A significant number of recorded dynamic events can be clearly and directly explained by the effects of the blasting works.

In order to assess the effectiveness of the provocation of the seismic events, the list of all tremors recorded between 2008 and 2014 within the G-4/8 mining panel were subdivided into two groups spontaneous and those provoked by blasting works. Fig. 15 shows the effectiveness of the high-energy seismic event provocation in terms of the number of observed tremors.

Fig. 16 shows the percentage of energy provoked by blasting works and released spontaneously from the rock mass.

The analysis indicates that the effectiveness of the provocation of dynamic events changed significantly over time. From the perspective of the number of events, the effectiveness varies from 8% to 17% on an annual basis. However, when considering the energy of tremors, it changes from 0.01% up to 60%.

4. Discussion

The comparision of mining face progress and the opening area in respect to observed seismic activity between 2008 and 2014 is shown in Fig. 17 and Fig. 18.

The quarterly value shows that the opening area has a greater impact on the total emitted energy of tremors than the quarterly progress of mining. Since the volume of the opening has a direct impact on the pace of roof deflection, the increase in the distance between the mining front and the mined out zone might have the effect of increasing cumulated energy above technological pillars. It may finally result in the increased energy of seismic events. An example of this might be the first quarter of 2012 when the highest amount of emitted energy ($E_s = 1.64 \cdot 10^8$ J) coincides with the greatest opening area. With a decrease in the opening area, a reduction of the total energy of tremors was observed.

As a result of the presented analysis, it was observed that the mining progress was connected to the number of recorded seismic events. This situation may suggest that the quarterly progress of the mining front disturbed the balance of the internal forces of the rock mass, which in turn leads to an increase in the number of tremors. The curve representing mining progress is consistent with the curve which represents the number of events in 25 of the 28 considered quarters.

5. Conclusions

The aim of this analysis was to determine the relationship between applied methods of rockburst prevention with recorded seismic activity in the G-4/8 mining panel of Rudna mine. Particular attention was paid to the pace of the development of mining works. This term is widely used in the mining industry and may be considered in two ways. On the one hand, it could consider the progress of the mining front only. On the other hand it could describe all of the works related to the development of the mining front and the advance of the mined out area. Therefore, both situations were analysed.

Within the framework of this paper, the effect of mining front advance and the opening area on seismicity was analysed. Consequently, it was concluded that a correlation between the opening area and the energy of seismic events may be observed under the mining panel conditions considered. A similar conclusion applied as regards the correlation between the quarterly speed of mining and the frequency of event occurrence.

Following analysis of the impact of the opening area on seismic activity, it was concluded that an increase in the frequency of dynamic events can be observed when the quarterly opening area

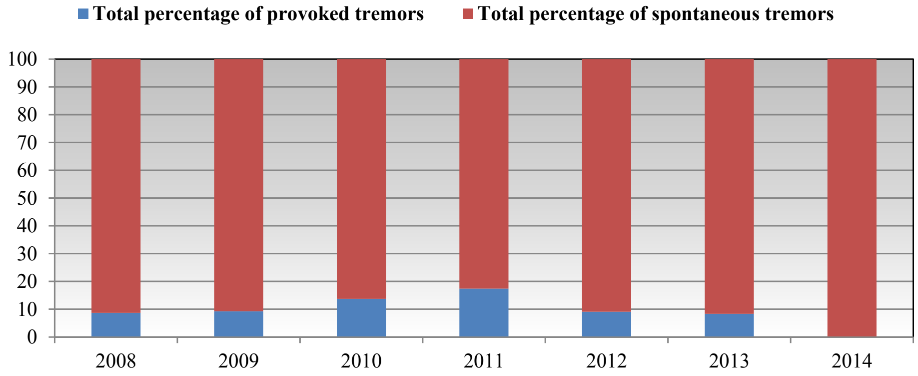

Fig. 15. The effectiveness of the high-energy event provocation within the G-4/8 mining panel between 2008 and 2014.

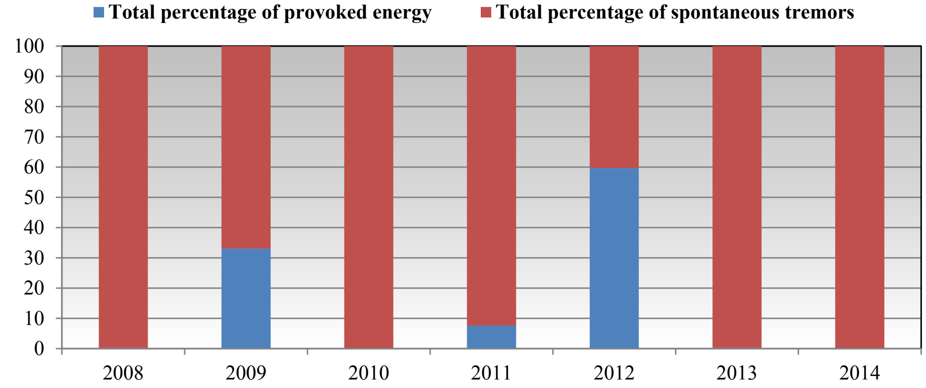

Fig. 16. The effectiveness of the high-energy event provocation within the G-4/8 mining panel between 2008 and 2014.

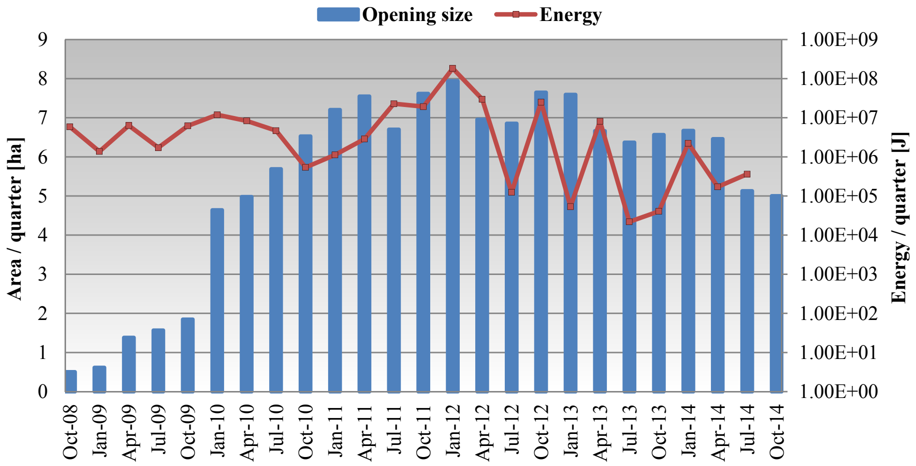

Fig. 17. The speed of a mining face's progress and the opening area correlated with released energy.

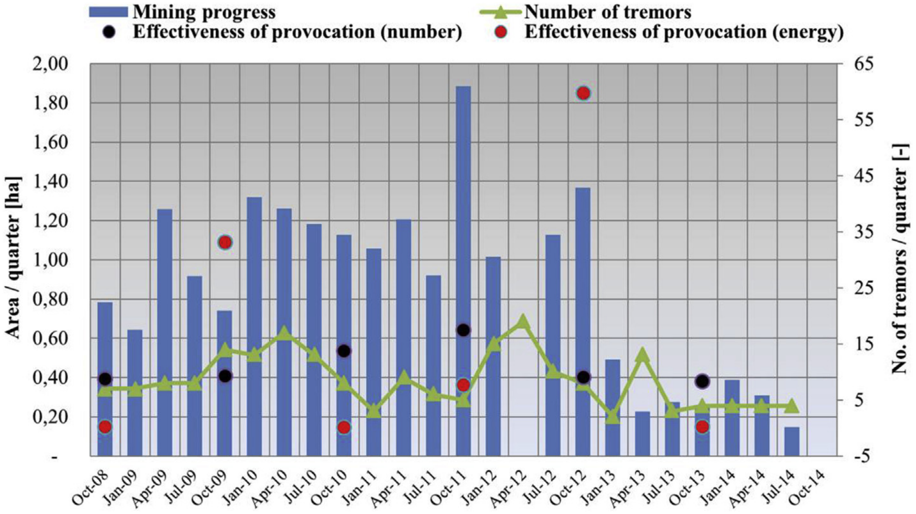

Fig. 18. The speed workings of progress and opening area in respect with number of induced events and active rockburst prevention G-4/8.

exceeded 6 ha. It is therefore justified to consider whether there should be a limit to the opening area, which affects the increased risk of seismic hazard. An analysis of the active rockburst prevention methods indicated that the effectiveness of high-energy event provocation remains at a low level in terms of both quantity and energy, excluding 2012 when the effectiveness of provocation reached 60%. This certainly confirms the need for the further development of this methodology.

Since no satisfactory results were achieved for the selected methods of rockburst prevention, there is a need for continued efforts to improve the effectiveness of these methods. Additional analysis should be developed for different mining panels located in different mining districts of copper mines belonging to KGHM to determine the degree of the correlation between the impacts of the speed of mining on the observed seismic activity. If similar conclusions are drawn, further analysis of the impact of other parameters concerned with applied mining technology on seismic activity should be considered, i.e. dimensions of the mining front and technological pillars, direction of mining, etc. This would provide more detailed information on the real influence of the selected parameters of rockburst prevention on seismic activity, which in turn may indicate some parameters of mining methods that need to be modified. Therefore, further development of mining works should be based not only on the experience of the crew but also on previously defined values.

Conflict of interest

None declared.

Ethical statement

Authors state that the research was conducted according to ethical standards.

Funding body

None.

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