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Novel approach for the destress blasting in hard rock underground copper mines

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Abstract

The present study investigates the possibility of developing a novel method for reducing seismicity and rockbursts in deep underground mines based on modifying drilling and blasting patterns. The main goal was to develop and implement firing patterns for multi-face production blasting, which allow increasing the capability of inducing stress relief in the rock mass, manifested in the seismic event. This method may improve stability control in underground workings, and mitigate risks associated with the dynamic effects of rock mass pressure compared with currently used methods. Thus, the seismic energy may be released immediately after blasting in a controlled way. For this purpose, underground tests using modified blasting patterns and precise electronic detonators were carried out. Vibration data recorded from the multi-face blasting in the considered trial panels were assessed in the scope of amplitude distribution. Results of trials have proven that the method is promising and should be further developed to improve the effectiveness of rockburst prevention in deep hard rock mines.

Keywords

rock mechanics, rockburst hazard, destress blasting, induced seismicity

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Novel approach for the destress blasting in hard rock underground copper mines

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Abstract

The present study investigates the possibility of developing a novel method for reducing seismicity and rockbursts in deep underground mines based on modifying drilling and blasting patterns. The main goal was to develop and implement firing patterns for multi-face production blasting, which allow increasing the capability of inducing stress relief in the rock mass, manifested in the seismic event. This method may improve stability control in underground workings, and mitigate risks associated with the dynamic effects of rock mass pressure compared with currently used methods. Thus, the seismic energy may be released immediately after blasting in a controlled way. For this purpose, underground tests using modified blasting patterns and precise electronic detonators were carried out. Vibration data recorded from the multi-face blasting in the considered trial panels were assessed in the scope of amplitude distribution. Results of trials have proven that the method is promising and should be further developed to improve the effectiveness of rockburst prevention in deep hard rock mines.

Keywords: rock mechanics, rockburst hazard, destress blasting, induced seismicity

1. Introduction

According to recent experiences, it may be stated that mining-induced ground control problems appear to be the most dangerous hazard associated with underground mining [1,2]. Such phenomena are very complex and extremely difficult to predict since ground failure mechanism varies depending on local mining and geologic conditions. This issue is hazardous for workers due to their direct exposure to geomechanical risks observed in the vicinity of active mining panels. Many hazards present in underground mining cannot be observed in other branches of industry. Events such as roof falls, gas outbursts, and induced seismic activity are global problems, but no fully effective mitigation measures are available. Therefore, despite implementing of different prevention measures, the risk for people, infrastructure and machines in underground space remains relatively high [3–5].

Bearing in mind the safety of employees, hazards of a dynamic nature may be classified as one of the most dangerous [6–8]. Special attention should be paid to rockburst phenomena, i.e. dynamic movement of rocks into openings caused by the rapid energy release from the rock mass. It creates a severe hazard for workers, machines, and facilities in the area prone to instability [9–11].

Currently, exploitation of deposit in deep mines is conducted in many cases at depths greater than 1000 m, where difficult geomechanical conditions and high stresses are observed [12,13]. With the progress of mining, a negative impact of created voids on the overall stress characteristic within the orebody may be observed. All these factors can lead to the accumulation of energy, the formation of overloaded areas, and in consequence the instability of workings [14]. The tendency to rockburst also depends on the type of rocks surrounding excavations, geologic discontinuities and applied mining method [15–17]. This issue is particularly important in the case of hard rock mining, which favours seismic events in

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the direct vicinity of workings due to high stresses within the roof stratum [18,19]. Therefore, proper management of such hazards is crucial to ensuring safe working conditions.

Many different methods can be applied to mitigate the risk of rockburst in underground mines. One such method is destress blasting, which seems to be one of the most effective. The effectiveness of this method has been proven in different underground projects, both in mining and tunnelling [20–23]. Rock mass damage and crack propagation induced by blasting play a significant role in the safety and stability of workings [24,25].

The purpose of destress blasting is to control the risk of rockburst hazard in the following ways:

- release the seismic energy accumulated in the rock mass (triggering of the seismic event) by the detonation of explosives in blastholes,
- reduce the rock's ability to stress accumulation by changing the mechanical properties from elastic to more plastic (damaging of rock structure).

This means, that the most important aspect of the destress blasting is the correct design and implementation in the relevant location and time. The rockburst hazard is also associated with the mining of the copper deposit in deep underground mines in Poland, where room-and-pillar mining method with roof deflection and pillar softening is used. The seismic activity in this area remains at relatively high level both in terms of the number of tremors and their energy [26]. A significant reduction of energy emitted from the rock mass was observed in 2007. Since then, the level of seismic activity has been relatively stable, but the total annual energy of tremors still ranges from $1\cdot10^9$ J to $3\cdot10^9$ J (Fig. 1).

When analyzing the data presented in Fig. 1, one may conclude that even if the total annual energy emitted from the rock mass is relatively stable, the level of rockburst hazard in Polish copper mines is still high. Therefore, many different preventive methods have been applied to reduce such a hazard. Existing methods are being improved continuously, but novel, more effective methods are also being developed. Nevertheless, recent experiences have proved that active methods with explosives appear to be the most effective [27–30].

According to the adopted mining method, blasting in Polish copper mines is performed twice a day, i.e. after the second shift (ca. 5:30–6:30 p.m.) and the fourth shift (ca. 5:30–6:30 a.m.). The scale of mining operations may be described by approx. 700 mining faces and more than 60 tonnes of explosives detonated each day. Destress blasting in turn is conducted in the form of a multi-face blasting, i.e. simultaneous firing of explosives in a group of faces (usually from 10 to 20) within one panel. Such an approach allows for a compromise between the rockburst prevention regulations and a high extraction rate. In this method, seismic waves generated by the firing of a large amount of explosives can lead to triggering of the seismic event shortly after the completion of blasting or within a waiting period in the absence of the crew in the area of blasting. The effectiveness of this method varies depending on the considered mining panel and reaches the level of about 30%. This indicates that there is still potential for improvement.

The Authors assumed that improvement of destress blasting methods may be achieved by modifying the drilling and blasting patterns (D&B) and synchronizing the delay times in the following faces, which should maximise the amplitude of the

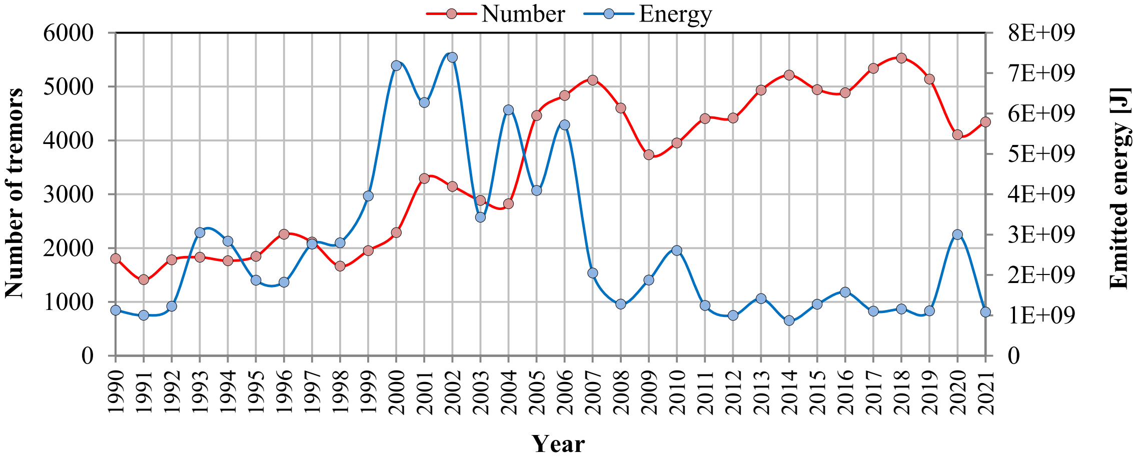


Fig. 1. Number and energy of tremors observed between 1990 and 2021 in Polish copper mines.

induced seismic wave. It may also be assumed that greater seismic energy has a higher potential to trigger the tremor and release elastic energy accumulated in the rock mass. Moreover, it should be noted that any modification to the D&B patterns aimed at improving the seismic effect of blasting may not affect the correct production outcome. A completely different method of destress blasting is practised in Polish and Czech coal mines in which the longwall mining method is used. In these cases, destressing is aimed at improving the seismic effect only, which significantly disturbs the production process due to the complicated and time-consuming procedure of blast preparation. Such works are performed in the form of a group of long blastholes located within the roof ahead of the longwall face [31,32].

In this paper, a novel approach for stress release blasting in the conditions of Polish copper mines has been proposed and verified during the in-situ trials. This approach consisted of modifications of D&B patterns in terms of increasing the charge per delay and increasing the initiation system's precision by applying electronic detonators. The effect of the proposed method has been analysed in terms of seismic amplitude distribution and triggering rate in comparison to the standard approach used in analysed mining panels.

2. Basic concept and approach

The general concept of the proposed approach is to increase the level of blasting induced seismic load and therefore increase the probability of seismic event triggering. The value of the surplus stress depends on the amplitude of the seismic waves, which can be characterised by peak particle velocity (PPV). According to Equation (1), the stress in the ideal case where a plane wave passes through an elastic material is proportional to the particle velocity [33]:

$$\sigma = \rho C v \tag{1}$$

where: σ – stress [Pa]; v – particle velocity [m/s]; C – wave propagation velocity [m/s]; ρ – rock mass density [kg/m^3].

The amplitude of vibration velocity (v) generated by blasting depends on the explosives charge per single delay, distance from the measuring site, and rock characteristic [34,35]. This relationship has been determined by Langefors and may be expressed by the following Equation [36]:

$$v = K\sqrt{\frac{Q}{R^{\beta}}} \tag{2}$$

where: Q – maximum charge per delay [kg]; R – distance [m]; K, β – site factors.

Therefore, amplification of the seismic effect may be achieved by maximising the charge per delay. This can be done by increasing the amount of explosives in blastholes, increasing the number of blastholes fired with the same delay, and increasing the number of fired faces.

However, the key factor influencing the possibility of wave amplification is the delay accuracy of detonators. The accuracy of mining electric and non-electric detonators is about ±10%. Nevertheless, since the delay element in these detonators is pyrotechnic, it can even reach 20% [37,38]. With such a low accuracy of delays, it may be expected that the firing time of the following blastholes will be disturbed or even random. This will cause the induced wave to be scattered and the seismic effect will be lower than expected. This issue is especially important when using decisecond or even half-second delay detonators instead of millisecond ones. In such a case, the deviation from a few to several dozen milliseconds affects a significant scattering of induced seismic impulse, which will translate into a lower destressing efficiency. In order to minimize this effect and increase the likelihood of simultaneous firing, short delay non-electric detonators should be used. Another method of initiating explosives in blastholes simultaneously is the application of precise electronic detonators. In this study, a hybrid firing method has been used, i.e., combination of non-electric and electronic detonators in the faces. The scheme of this kind of blasting circuit is shown in Fig. 2.

It should be noted that the primary expectation from such a blasting, apart from destressing, is to obtain the proper outcome in terms of both correct advance and rock fragmentation. Thus, the scope of changes of delays was limited.

3. Materials and methods

Demonstration of the proposed method was conducted in two mining panels located in two mines belonging to KGHM Polska Miedź S.A. (one panel for each mine). The selection of the panel was based on two factors: (1) a high level of seismic activity and (2) the relatively regular shape of the mining front. It was assumed that such conditions should allow triggering the seismic event during the faces firing

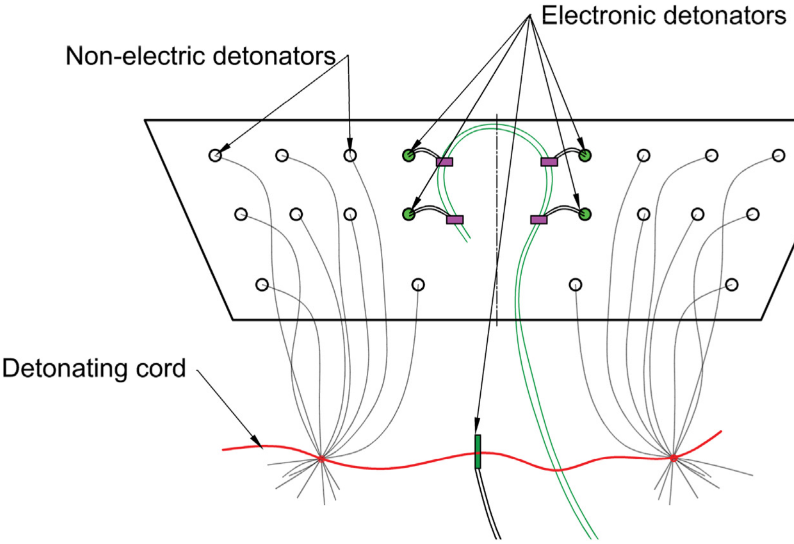


Fig. 2. Scheme of blasting circuit with electronic and non-electric detonators in the face.

or within the so-called waiting period after completion of blasting. Two trials were conducted on each site. The efficiency of trials was assessed in terms of tremor triggering, i.e., occurrence of the seismic event at the moment of firing or shortly after completion of blasting. All the tests were performed using E*Star electronic detonators manufactured by Austin Powder.

3.1. Description of trial panels

The flat copper deposit in both panels is excavated using the room-and-pillar mining method, which seems to be well adopted to the geometry of the orebody. The geologic structure observed there favours the occurrence of seismic events. This is mainly because the roof stratum is usually formed from strong dolomite characterized by high strength (UCS up to 250 MPa) and low deformability. In turn, the floor stratum consists of much weaker sandstone (UCS of 30–100 MPa). Under such conditions, the elastic energy is accumulated in the roof stratum, what is usually manifested by the release of energy in the form of seismic event.

Panel A was located in the Rudna mine. The orebody with an average thickness of about 2.2 m is formed from sandstone, copper-bearing shales and dolomite. The roof stratum consists of strong dolomite with an average thickness of 15 m. In turn, the floor stratum consists of sandstone with a thickness exceeding 300 m. Excavations within this panel are located at a depth of 1160 m below the surface (on average) and inclined at 2–3° in NE direction. The scheme of excavations in the vicinity of the considered panel is shown in Fig. 3. Green zones on each figure indicate the mined-out area, white is the

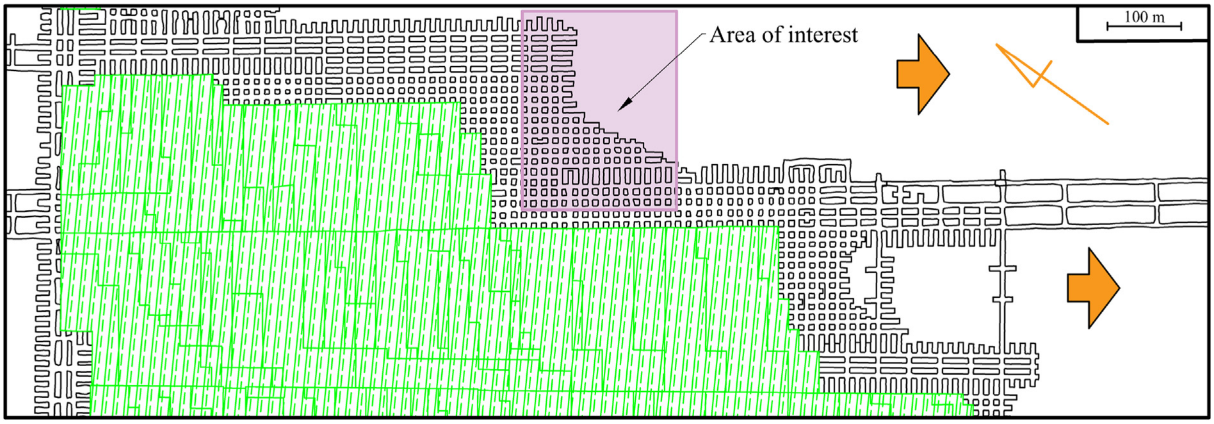


Fig. 3. Geometry of excavations in the vicinity of panel A.

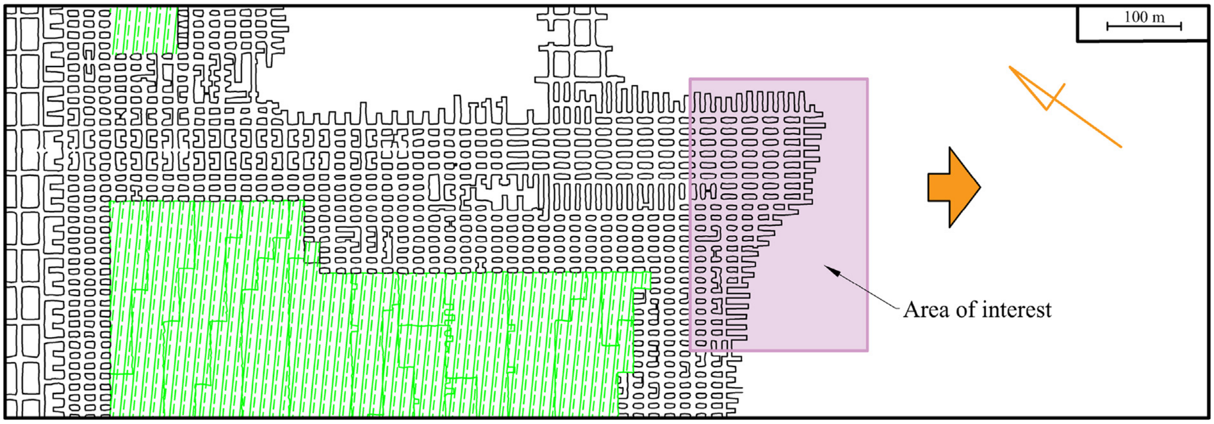


Fig. 4. Geometry of excavations in the vicinity of panel B.

undisturbed rock mass and the orange arrows show the direction of mining.

Panel B was located in the Lubin mine. The copper deposit in this area, with an average thickness of approximately 1.8 m, contains sandstone and copper-bearing shales. The roof stratum comprises dolomite and limestones with an average thickness of ca. 70 m. The floor consists of sandstone with a thickness exceeding 300 m. The copper-bearing deposit is located at a depth from 760 to 830 m below the surface and is inclined at 3–5° in N direction. The scheme of excavations in this area is shown in Fig. 4.

3.2. Seismic activity

In order to evaluate the rockburst hazard in the vicinity of the trial panels, the seismic activity in the period of 6 months prior to underground tests was analysed. In this period, 30 seismic events were recorded within panel A. When analysing the seismicity in this panel, one may conclude that the tremors most often occurred in month 1. Then, a significant drop in the monthly number of tremors of about 60% was observed. Such a situation remained stable until sixth month. In turn, when analysing the energy distribution, the highest seismic intensity occurred in third month, when the total monthly emitted energy exceeded the value of $1.2 \cdot 10^7$ J. After that, a stable decrease in seismic activity in the following months may be noticed (Fig. 5).

Provocation levels in the energy domain varied from 0.1 to 97% (23% on average). Correlation between triggered energy and the number of provoked tremors was not observed. This led to the conclusion that the process was stochastic and out of control. The analysis showed that the overall efficacy of tremors triggering over the six-month period achieved an average provocation level of 54% in terms of quantity and only 3% in the energy domain. Such a situation confirms that there is still great potential to improve the provocation level in this panel.

Seismic activity in panel B remained rather high in the analysed period both in terms of the number of events and their energy (Fig. 6). It should be noted that the total seismic energy emitted in this area in each considered month exceeded $1.3 \cdot 10^6$ J. Such a high level of seismic activity may be one of the indicators of the risk of roof falls and rockburst.

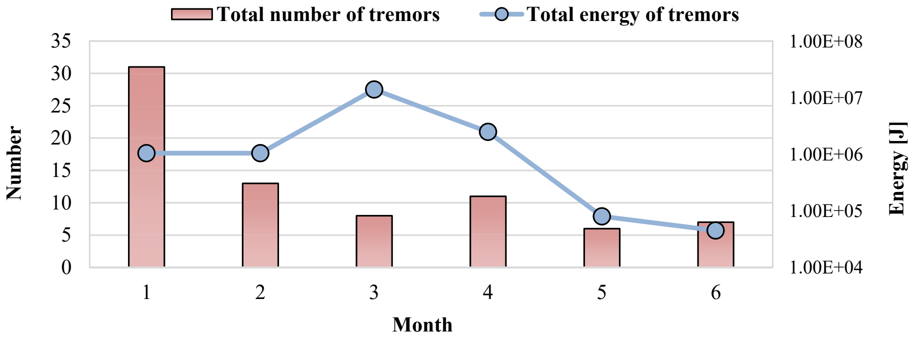


Fig. 5. Distribution of tremors observed in Panel A in the six-month period before trials (energy > 10^3 J).

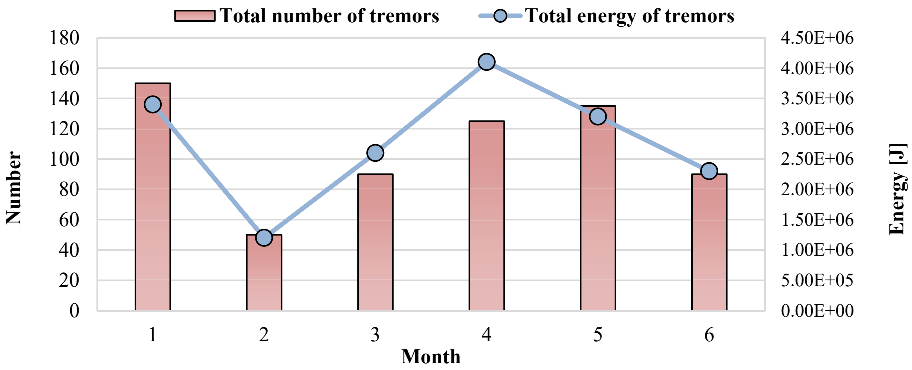


Fig. 6. Distribution of tremors observed in Panel A in the six-month period before trials (energy > 10^3 J.).

Group blasting was applied as the basic preventive method during the analysed period. Unfortunately, the triggering rate related to these blasts was very low both in the quantitative and energy domains. From the quantitative point of view, the average effectiveness was approximately 13%, and only 8% in relation to the energy. This clearly indicates that most seismic events were spontaneous (natural) and unrelated to the stress release blasts.

3.3. Seismic data collection

Observations of seismic events were based on the recorded vertical components of the vibration velocity at four seismic posts located around analysed panels. Measurements were made using the Willmore MK IIIA seismometers with a frequency band in the range of 0.1–150 Hz. The sampling frequency was 500 Hz. The distances between blasting faces and seismic posts in the analysed panels ranged from 500 to 1700 m.

4. Underground trials

For the purpose of the analysis within panel A, two trials were carried out. In addition, one standard blast was conducted prior to the trials in order to collect the seismic reference records. The standard D&B pattern and non-electric detonators were used in the reference blast and modified D&B patterns and electronic detonators (in selected blastholes) in two specific trials. In all cases in panel A, a parallel cut with empty holes was applied. The length of blastholes was 3 m and a diameter of 48 mm. The diameter of empty holes located in the centre of the cut was 89 mm in trial #1 and 48 mm in trial #2. Blastholes were loaded with chemically sensitized bulk emulsion explosive. Faces locations in each blast are shown in Fig. 7. Trials included the

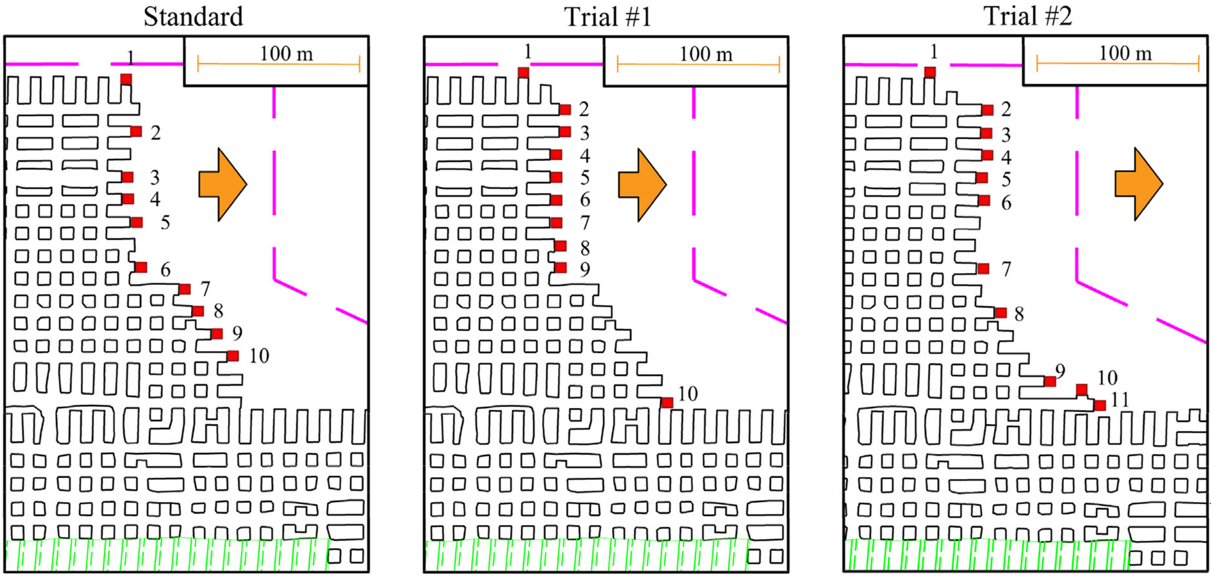


Fig. 7. Geometry of mine workings and location of fired faces within panel A.

firing of 10 and 11 faces, respectively, and 10 in the standard blast.

Modifications of the standard blasting pattern in trial #1 included reducing the total firing time from 3000 to 1600 ms, and increasing the number of blastholes initiated with the same delay from 4 up to 7. Thanks to this, a maximum charge per delay in the entire group was increased by 36%, i.e., from 180 to 245 kg. The total number of holes was 34 (including two empty holes). Holes were located in a sandstone and dolomite stratum (no holes in the shales). Electronic detonators were loaded into seven blastholes and fired as the second group of holes after the cut. Explosives in other holes were initiated using non-electric detonators. All electronic detonators were programmed with a delay time of 700 ms. The total amount of explosives in a single face was 122 kg (1220 in total) and the maximum charge per delay was 24.5 kg (245 kg for the entire blast).

In trial #2, the total firing time was extended from 1600 to 3000 ms. The drilling pattern consisted of 30 holes (including three empty). Electronic detonators were loaded into specified seven holes, programmed with a delay time of 1000 ms and fired as the second group of holes after the cut. Explosives in other holes were initiated using non-electric detonators. In this trial, the charge per delay increased by approx, i.e., from 180 to 269.5 kg. The applied delays, location of holes and the amount of explosives in individual holes for both trials in the Rudna mine are presented in Fig. 8.

The total amount of explosives in a single face during trial #2 was 100.5 kg. In turn, the maximum charge per delay was the same as in the trial #1, i.e., 24.5 kg. Selected blasting data for both trials are presented in Table 1.

Two trials were carried out in panel B, similar to trials in panel A. They were also preceded by one standard blast in order to collect the seismic reference records. Standard D&B pattern and non-electric detonators were applied in reference blast, and modified D&B patterns and electronic detonators in two specific trials. The total number of holes in each face in panel B was 29, including four empty roof protection holes (27 blastholes in the standard pattern). The length of each blasthole was 3 m and the diameter of 51 mm (same diameter for empty

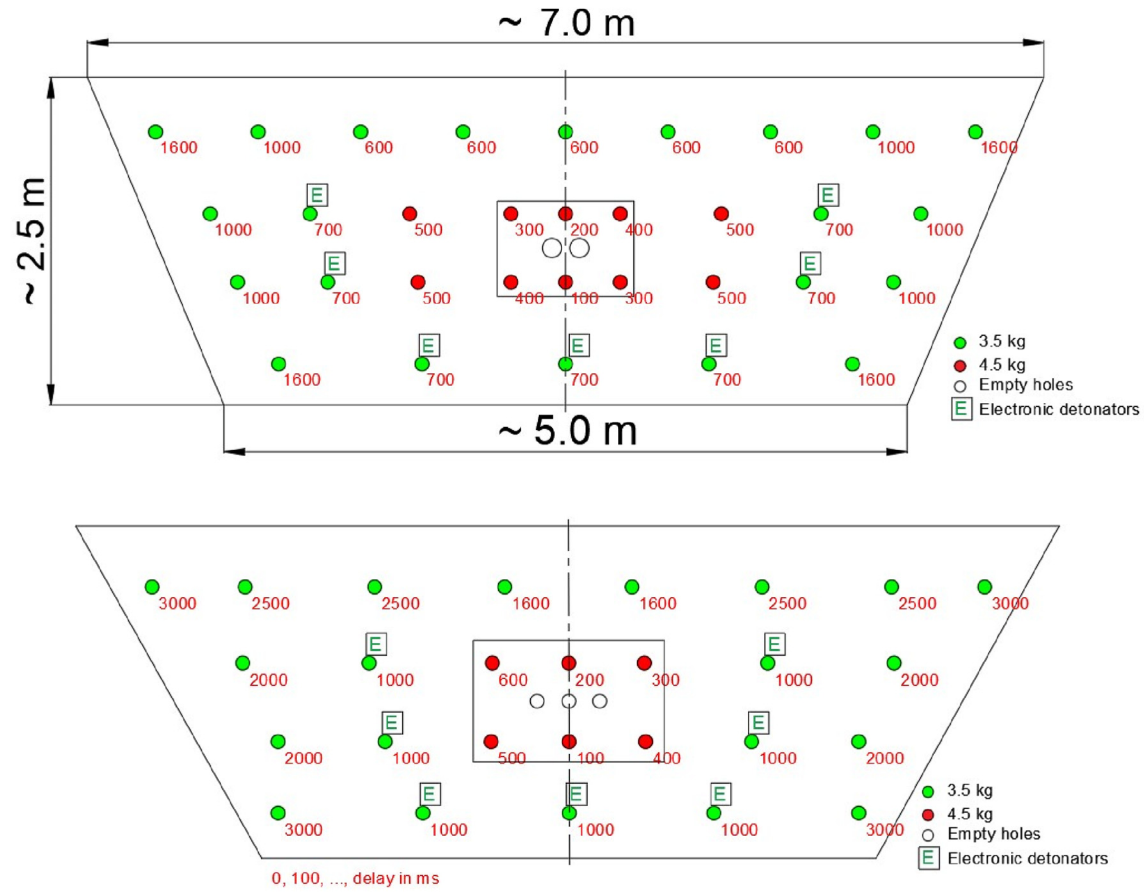


Fig. 8. Drilling and firing patterns applied in trial #1 (top) and trial #2 (bottom) – panel A.

Table 1. Selected blasting data for the trials in panel A.

Parameter		Number of faces	Total amount of explosives [kg]	Maximum charge per delay [kg]	Powder factor [kg/tonne]	Total blasting time [ms]
Standard blasting	Face	10	115	18	0.99	3000
	Group		1150	180		
Trial #1	Face	10	122	24.5	1.05	1600
	Group		1220	245		
Trial #2	Face	11	100.5	24.5	0.87	3000
	Group		1105.5	269.5		

holes). All blastholes were located in the sandstone stratum (no holes in the shales). In all faces in this panel, the V-cut consisting of six holes was applied. Locations of faces in each blast are shown in Fig. 9. Trial #1 included the firing of 11 faces, trial #2—10 faces, while 11 faces were fired in the standard blast.

During the first trial in panel B, modifications of the standard blasting pattern consisted in adding two additional blastholes in the V-cut in each face in the group. It allows to increase the number of blastholes initiated with the same delay from 4 to 6 and increase the maximum charge per delay in the entire group by 50%, i.e. from 154 to 231 kg. Electronic detonators were loaded into six holes in the V-cut. Explosives in other holes were initiated using non-electric detonators. All electronic detonators were programmed with 0 ms initiation time (no delay). Blastholes were loaded with chemically sensitized packaged emulsion explosive. Applied delays, location of holes and the amount of explosives in individual holes are presented in Fig. 10. The total amount of explosives in a single face was 73.5 kg (808.5 kg in total) and the maximum charge per delay was 21 kg (231 kg for the entire blast).

In the trial #2, the total firing time was reduced from 5000 to 1500 ms. The location of blastholes, the lengths and diameters, as well as the location of electronic and non-electric detonators were the same as in the first trial. All electronic detonators were programmed with 0 ms initiation time (no delays). In this case, all blastholes were loaded with chemically sensitized bulk emulsion explosive. The maximum charge per delay was reduced by ca. 10% compared to trial #1, i.e., from 231 to 210 kg what was related to a lower number of faces, but increased by 36% in relation to the standard blast. The applied delays, location of holes and the amount of explosives in individual holes for both trials in the Lubin mine are presented in Fig. 10.

The total amount of explosives in each face during trial #2 was the same as in trial #1, i.e., 73.5 kg (735 kg in total). The maximum charge per delay was also the same (21 kg), but the maximum charge per delay for the entire group was 210 kg. Selected

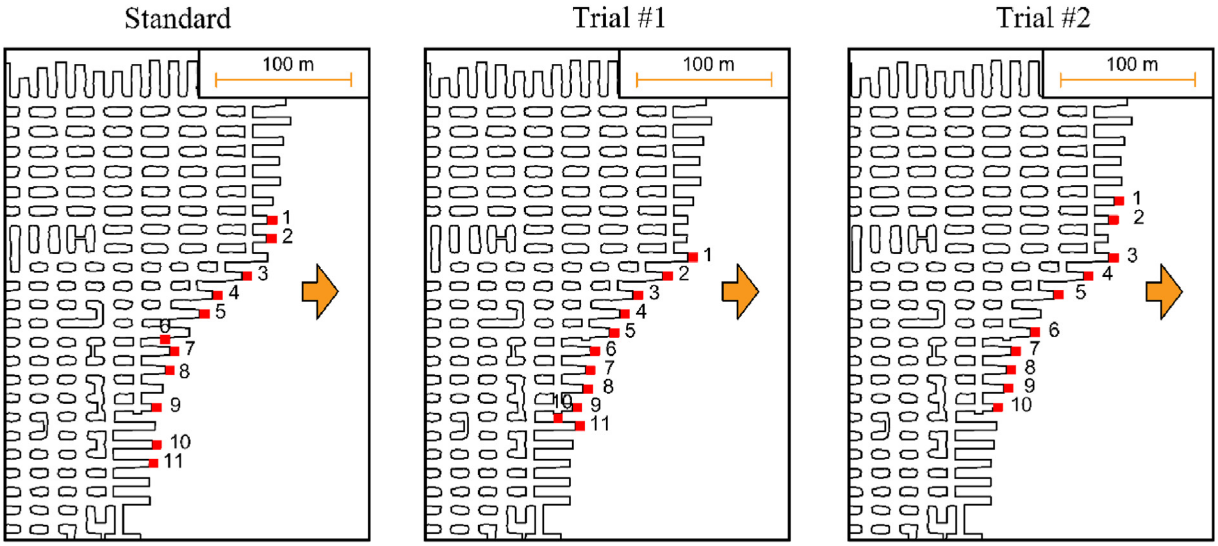
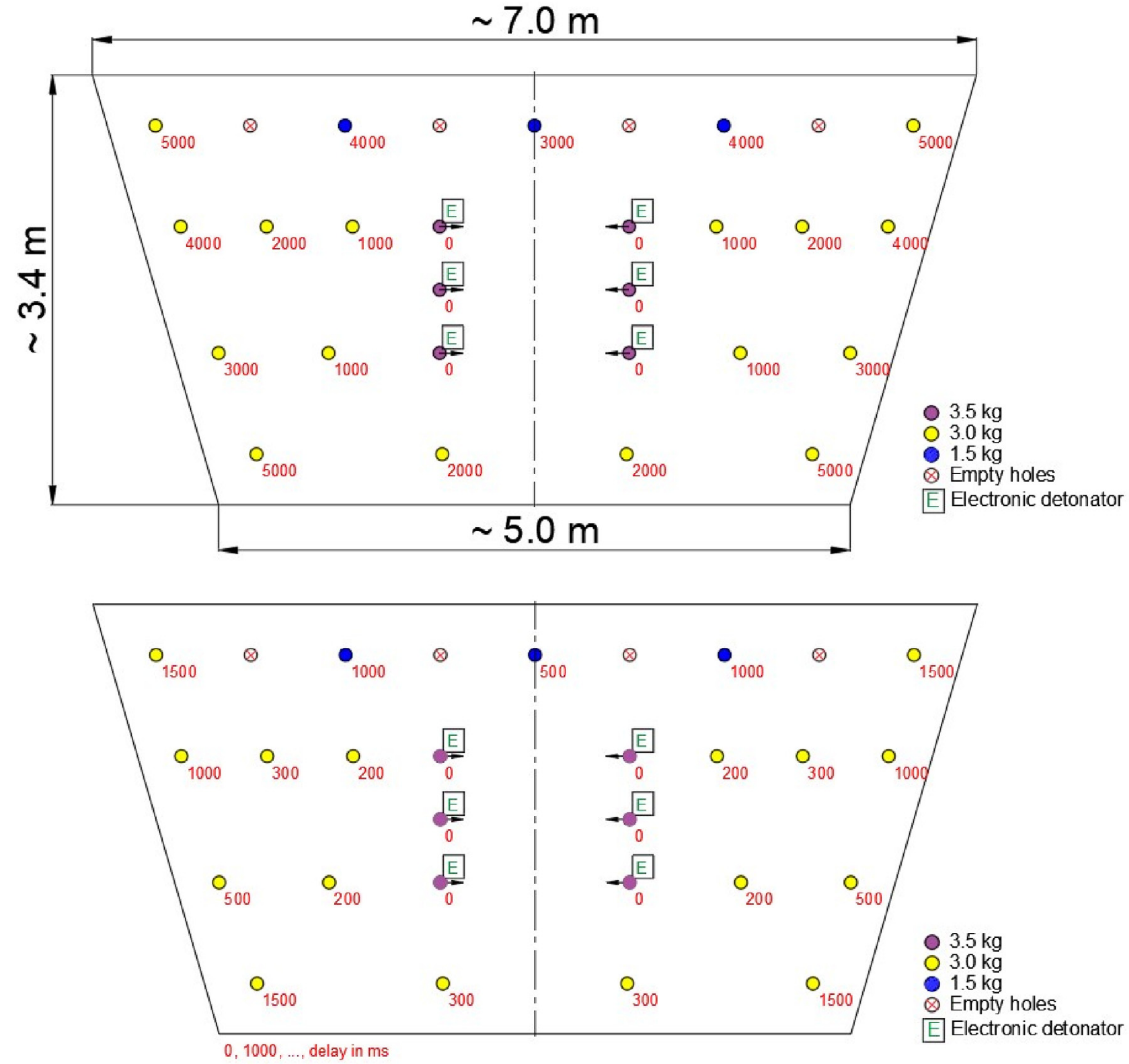


Fig. 9. Geometry of mine workings and location of fired faces within panel B.



0, 1000, ..., delay in ms

Fig. 10. Drilling and firing patterns applied in trial #1 (top) and trial #2 (bottom) — panel B.

blasting data for both trials in panel B are shown in Table 2.

5. Results and discussion

Evaluation of the destress blasting efficiency was based on the triggering rate of seismic events and analysis of the amplitude of induced vibration after each blast. The occurrence and location of tremors were determined using the local seismic network. Analysis of the data recorded during the tests in panel A showed that three seismic events were provoked by blasting. On the other hand, blasting with the standard D&B pattern did not trigger any

Table 2. Selected blasting data for the trials in panel B.

Parameter		Number of faces	Total amount of explosives [kg]	Maximum charge per delay [kg]	Powder factor [kg/tonne]	Total blasting time [ms]
Standard blasting	Face	11	75	14	0.54	5000
	Group		825	154		
Trial #1	Face	11	73.5	21	0.53	5000
	Group		808.5	231		
Trial #2	Face	10	73.5	21	0.53	1500
	Group		735	210		

Table 3. Seismic events provoked in panel A.

Event no.	Trial no.	Energy [J]
1	#1	$1.1 \cdot 10^3$
2	#2	$2.8 \cdot 10^3$
3		$1.0 \cdot 10^3$

event. The list and energies of the events provoked during the trials in panel A are presented in Table 3.

The total energy of recorded tremors was approximately $4.9 \cdot 10^3$ J. Effectiveness of the trial blasts in the quantity domain was relatively high and reached 1.5 events per trial. Epicentral location of provoked event no. 3 is presented in Fig. 11. It was located about 130 m above the level of excavations, within the immediate roof stratum. Determination of other events' locations was impossible since they occurred at the moment of faces firing.

According to national regulations, tremors classified in E3 and E4 energy classes (seismic energy between $1.0 \cdot 10^3$ J and $9.9 \cdot 10^4$ J) are considered as low energy events. However, the possibility of high energy tremor triggering is not only related to parameters of blasting but also to the current geomechanical state of rock mass in the surrounding of considered panel. Therefore, the distribution of the seismic energy in the analysed period shall also be taken into account. The seismic energy distribution during the period of trials in panel A is shown in Fig. 12.

Based on the seismic activity observed over a period of trials in panel A, one may conclude that the level of seismicity was relatively low a few days before each trial. Within that period, a large variation in the frequency of tremors occurrence may be observed. Evaluation of the trends in seismic activity before trials may be expressed by the 5th-grade polynomial trend line (Fig. 12). Approximately one week before the first trial, a very low level of seismicity was observed. Then, ten days after the first trial, there was a significant increase in the energy of individual tremors. A high level of seismic activity within panel A was observed during the next 20 days. After that, the total energy of mining tremors dropped and relatively low seismicity was observed for the next 11 days. Then, a second trial

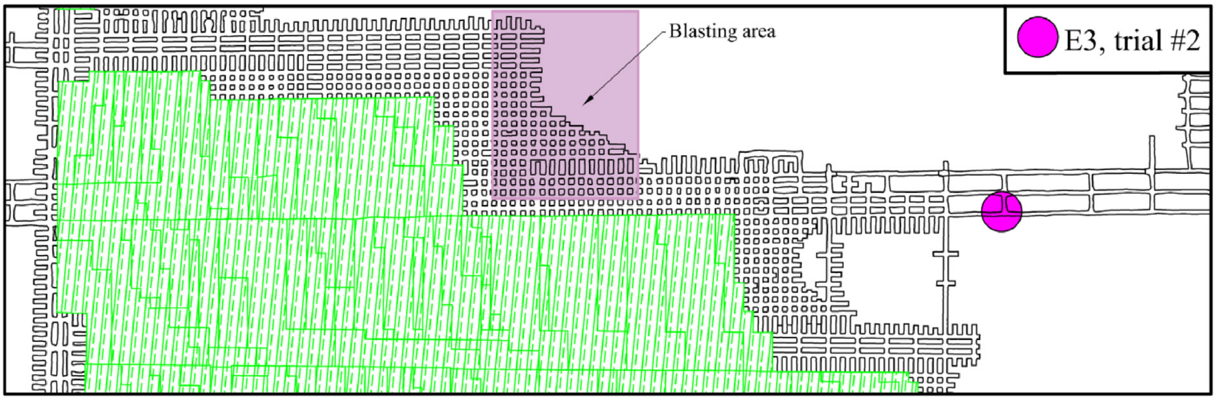


Fig. 11. Location of the seismic event provoked by trial #2 in panel A.

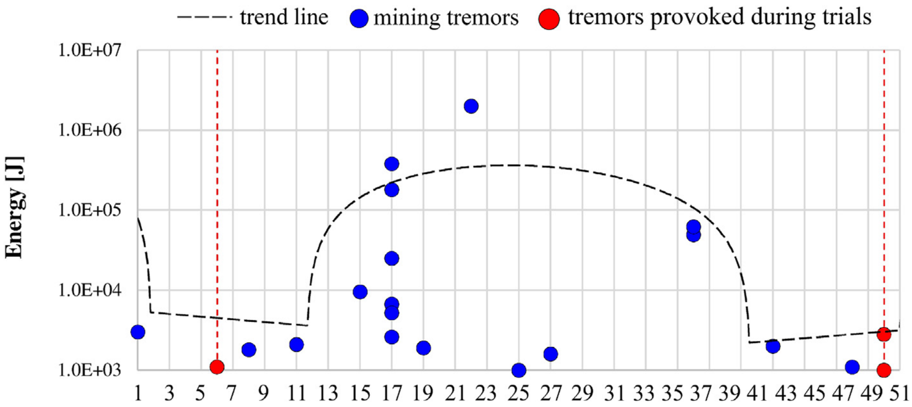


Fig. 12. Energetic distribution of mining tremors in panel A.

Table 4. Seismic events provoked in panel B.

Event no.	Trial no.	Energy [J]
1	#1	$6.7 \cdot 10^4$
2	#2	$2.6 \cdot 10^3$
3		$5.1 \cdot 10^3$

was carried out, as a result of which, two seismic tremors were provoked.

The distribution of seismic energy generally proves that the number and energy of tremors depend on the actual stress conditions of the rock mass in the vicinity of the considered panel. If rock mass is overloaded, then the energy and frequency of triggered and spontaneous tremors are usually high. In turn, if the rock mass is preconditioned by blasting, fractured, or not formed from high strength rocks, then the distribution of seismic energy will be much lower.

The satisfactory results of trials in the field of triggering of seismic events were also observed in panel B, in which three tremors were provoked by blasting. One tremor was provoked after the first trial and two after the second. In turn, the group blasting with the standard D&B pattern did not provoke any seismic event. A list of provoked events and their energies are presented in Table 4.

According to Table 4, the greatest energy of $6.7 \cdot 10^4$ J was emitted from the rock mass as a result of the first multi-face blasting. Energies of other tremors were slightly lower – both classified in E3 energy class. All provoked events were located within the immediate roof stratum on the following depths: event 1–668 m below the surface (162 m above the level of excavations), event 2–671 m (159 m), and event 3–653 m (177 m). They occurred 2 minutes after the faces firing in trial #1, and 1 and 11 minutes after firing in trial #2, respectively. The epicentral locations of all provoked tremors in panel B which were observed within the waiting period are presented in Fig. 13.

In order to determine the general trend of tremors energy distribution over time, the 6th-grade polynomial trend line was calculated (Fig. 14). The red dashed lines indicate the time of trials. As it may be observed, the energy of tremors provoked during the trials correlates with the overall level of seismicity. Therefore, knowing that the total energy released from the rock mass may be related to the actual stress condition, it may be concluded that performed trials were effective. According to Fig. 14, the seismicity trend before the first blasting remained very high. As a result, a strong tremor with the energy of $6.7 \cdot 10^4$ J was provoked. During the second trial in panel B, two tremors were provoked. These seismic events were generally characterised by low energy. Nevertheless, when analysing the trend of the daily energy emission, a low level of seismicity can be observed on the day of the trials. Therefore, it is clear that the energy of the triggered tremors correlates with the general trend of seismicity.

Finally, during four underground demonstrations in the area of mining panels with relatively high seismic activity, six tremors were provoked. All triggered events were observed after the firing of a group of faces with modified D&B patterns. In the case of standard blasting in the analysed area, no events were provoked. Consequently, the effectiveness of the proposed approach in terms of

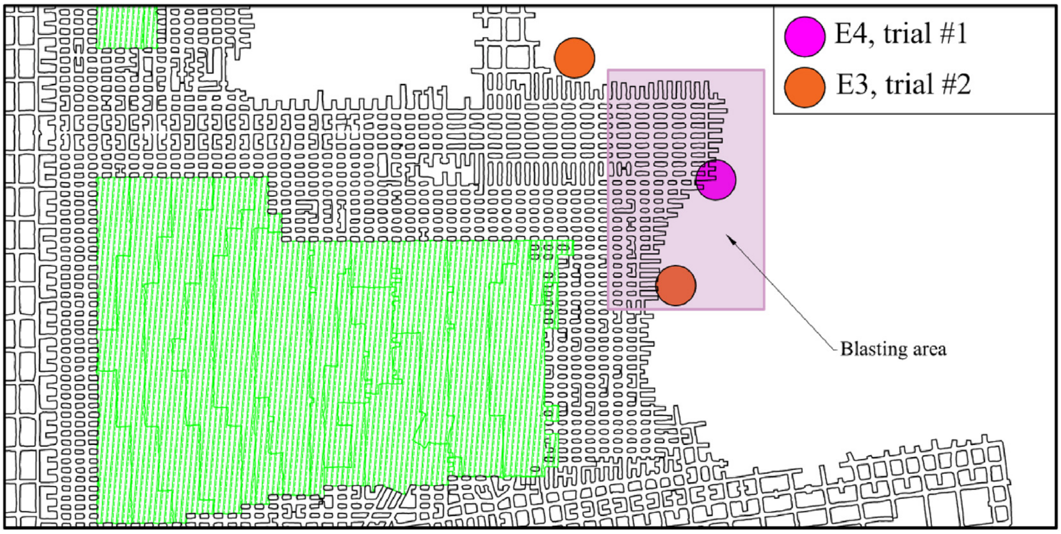


Fig. 13. Locations of the seismic events provoked by trials in panel B.

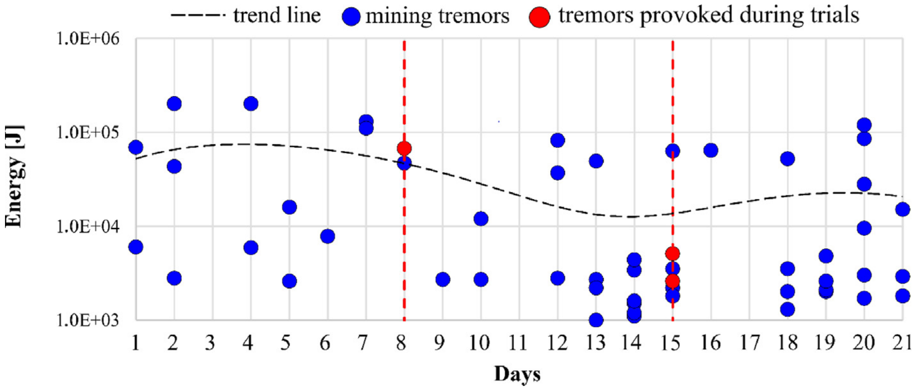


Fig. 14. Energetic distribution of mining tremors in panel B.

provoking rate in the quantity domain reached an average of 1.5 events per one trail blast, which seems to be very promising. However, the provocation rate depends not only on parameters of destress blasting but also on the current geomechanical state of the rock mass. Therefore, in order to increase the reliability of the presented results, the effect of blasting was also analysed in terms of the amplitude distribution. For this purpose, the amplitudes of the velocity of seismic waves generated by blasting were compared with the amplitudes induced by standard blasts in the analysed panels. The maximum amplitudes of the seismic wave velocity recorded at seismic stations located at the shortest distance from the seismic source are presented in Fig. 15.

From the above analysis, one may conclude that the application of precise electronic detonators and

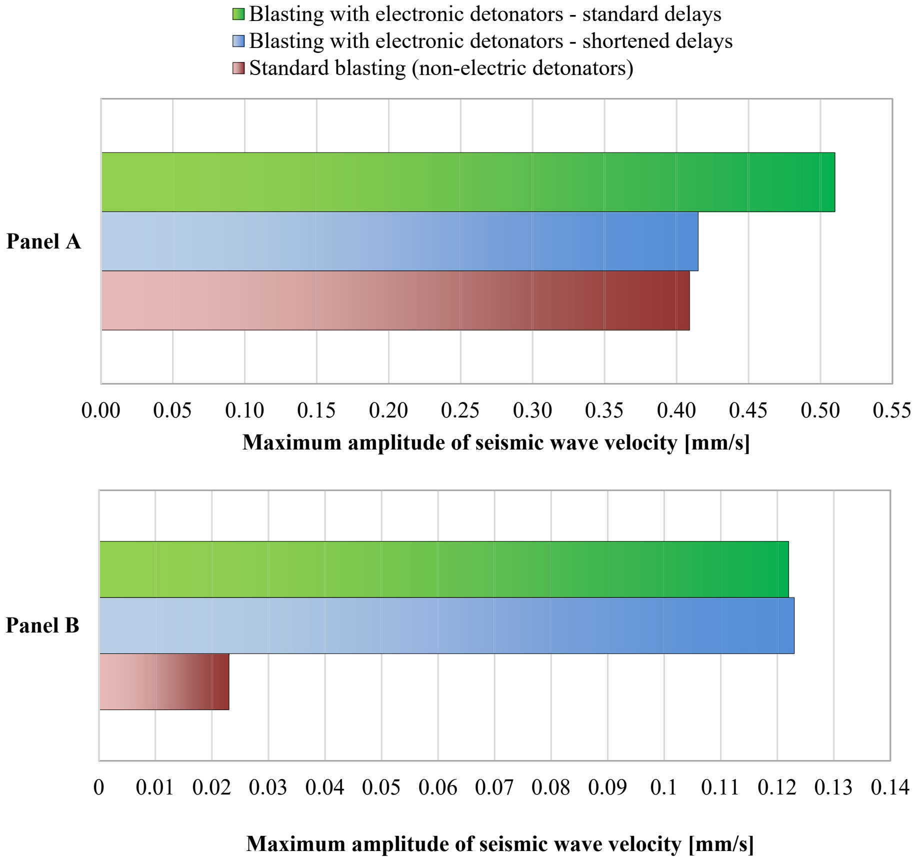


Fig. 15. Comparison of maximum amplitudes of vibration velocity for different trials.

modified D&B patterns resulted in an increase in the amplitudes of seismic waves in comparison to standard blasting with the use of non-electric detonators. It should be emphasized that the amplitude level recorded in each panel depends on the epicentral distance between the seismic source and the seismic station. This means that the amplitudes recorded on different panels should not be compared.

In the case of panel A, applying of a modified blasting with electronic detonators and shortened delay times resulted in an increase in the amplitude level by about 1.5% in relation to the standard blasting, which did not meet the expectations the seismic efficiency of destress blasting. A significant increase in the seismic effect was observed in the case of blasting with electronic detonators and standard delay times. Such modification translated into an increase in the amplitude of seismic waves by about 25%.

In the case of panel B, the use of electronic detonators and modified D&B patterns led to an increase in the seismic amplitude of more than 430% (in both trials) compared to standard group blasting. This confirms that a slight modification of the charge per delay and high-accuracy detonators allow control the time of maximum amplitude distribution.

The presented study should be treated as preliminary research on increasing the effectiveness of destress blasting in terms of triggering rate while maintaining the expected production rate. Despite the limited number of trials, one may conclude that the proposed approach has the potential to improve the ground control in deep underground mines. This is because, on the one hand, each trial triggered the seismic event, and on the other hand, there was a clear relationship between the applied delays and the amplitude of the recorded paraseismic waves. It should also be noted that modifications of destress blasting parameters were only focused on increasing the charge per delay and using more accurate electronic detonators. It is worth mentioning that the above changes do not affect production results. Visual assessment of the outcome from each blast confirms that both advance and fragmentation were correct. Thus, it may be concluded that the proposed approach has no negative impacts on the overall mining process.

6. Conclusions

The results of the presented trials confirmed that electronic initiation systems may be used to improve the effectiveness of active rockburst prevention methods in the conditions of Polish copper mines. Modifications tested during trial blasts should be treated as the basis for changes to the currently applied destress blasting methods in order to release the energy accumulated in the rock mass in the form of an induced tremor. The application of electronic detonators enables a precise delay time of firing and provides the real maximum charge per delay. It is possible to control the seismic impulse transferred to the rock mass based on this. Its amplitude may be much greater than generated using the current methods. The capabilities of electronic detonators (accuracy and programmability) ensure that the presented approach will be characterized by high repeatability and will allow to maintain a high level of destress blasting effectiveness.

Trial blasts have also shown that even small modifications to the D&B patterns have visible and positive effects in preventive blasting. A significant advantage of the presented approach is a relatively simple and quick implementation in regular mining operations. During a series of underground trials, six seismic events were observed. Even though the energies of events were relatively low (10^3–10^4 J), they were provoked by the simultaneous firing of faces. It means that each trial proved the effectiveness of group blasting in the rockburst prevention. The proposed method may increase intentionally induced seismic events and reduce spontaneous (hazardous) events. The results of the presented approach are promising and therefore, should be further developed to improve the effectiveness of rockburst prevention in deep hard rock mines.

Conflict of interest

The authors declare no conflict of interest.

Ethical statement

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

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