Seismic activity induced by exploitation in vicinity of mined-out space, case study from deep copper ore mine in Poland

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Abstract. Rock bursts are one of the most difficult to recognize and assess natural hazards in deep copper ore mines in Poland. The occurrence of rock bursts is conditioned by a number of complex geological and mining factors. The impact of each of the factors on the state of seismic hazard is sometimes impossible to be determined. The correct recognition of the rock mass condition and the causes of rock burst threat gives a chance for advance preparation of adequate prevention, and thus for eliminating or reducing the threat to the level of tolerated risk. In Poland's copper ore mines, continuous observation of seismic activity is carried out, which is expressed in the number of tremors and their energy over a specified period of time. Moreover, the effectiveness of prevention measures and, in particular, of the active ones, which are aimed at provoking seismic energy emissions through properly executed winning blasting works, is calculated and analysed. Reducing the amount of energy accumulated in the rock mass reduces the risk of rock bursts. Exploitation is carried out in a way that avoids parallel approach of the operational front towards the goafs, drifts, and faults with drops greater than the height of the mined deposit. However, over forty years of mining of the copper ore deposit, which has created the large areas of mined-out space mean that mining works are increasingly carried out under restrained conditions. There are unfavourable geological and mining situations in the exploitation fields, disrupting rhythmic development and an even front line. The specific structure of the copper ore deposit in Poland makes it possible to conduct multidirectional cutting and to introduce local changes in the adopted directions of exploitation. Cases of operational fronts approaching goafs occur often in the vicinity of old mining infrastructure and when there is the need to mine remnant parts of the deposit not previously intended for exploitation or not mined yet. Generally, exploitation in the direction of goafs or yielding zones is limited to the cutting and yielding works. The purpose of the study was to analyse the seismic and rock burst hazard in an exploitation field located at a depth of 850 m in a copper ore mine, over a period of 5 years, when mining was carried out towards goafs. Seismic activity and the effectiveness of rock burst prevention measures were assessed and analysed. The active prevention i.e. the group winning blasting works was an inseparable element of the excavation technology. It was found that when the operational front progressed towards adjacent goafs, there were symptoms of an increase in rock mass pressure causing the destruction of roof rocks and, as a consequence, deterioration of roof stability, squeezing of floor, relaxation of the side walls and increase of seismic activity, which posed the potential threat of rock bursts.
1. Introduction

In Polish copper ore mines i.e. Lubin, Rudna and Polkowice-Sieroszowice ones, which belong to the KGHM Polish Copper JSC, seismic tremors and rock bursts have posed the most hazardous phenomena since the first year of mining. The seismic threat means abrupt release of seismic energy, caused by deterioration of the rock mass strain balance. Seismic tremors can be triggered by natural factors such as geological ones or by mining operations. Tremors arising during excavation are considered as mining-induced tremors. In the copper mines in Poland tremors and rock bursts are divided into two categories as follows: spontaneous, which are induced by operational works or provoked (blasting-induced), which are induced designedly with winning blasting works to reduce energy stored in rocks and therefore to alleviate the strain and stress in a rock mass. In the Polkowice-Sieroszowice mine, which operates in Polkowice, Sieroszowice and Radwanice East mining areas, the number of rock bursts has been significant as about fifteen of them have occurred yearly on average for forty eight years. Such seismic hazard needs to be controlled by means of preventive measures which are implemented into the mining technology [1, 2].

Rock bursts are one of the most difficult to identify and assess natural threats because they are conditioned by a number of factors of complicated nature and contribution to the threat in given geological and mining conditions. The KGHM’s mines conduct continuous monitoring of seismic activity takes on and preventive measures, which include: assessment of the rock burst hazard, active, technological and organizational-technical preventive measures to reduce the risk, as well as assessment of this prevention efficacy. An appropriate exploitation project is considered to be the most efficient and cheapest preventive measure as well as the adequate mining technology and immediate and organizational activities together with continuous monitoring of the threat. Copper ores are mined with the use of blasting technology. Active preventive operations, which include the group winning blasting of the maximum number of faces, winning-relaxation blasting in advance of a front line, and blasting in a floor are considered the most efficient preventive measure [2, 3, 4].

Exploitation should be conducted in the manner avoiding parallel approach of the operational fronts to goafs, workings and faults with drops bigger than the thickness of deposit. Unfortunately, about fifty years of exploitation of the copper ores have created the large mined-out areas, which made mining to be often carried out under more and more restrained conditions. The geometry of opening excavations adapted to the structure of the deposit and technological rock burst prevention, consisting in making communication and transport excavations yield, leads to more and more frequent cases of leaving the deposit remains located in the vicinity of goafs and yielded zones. Moreover, in the exploitation panels, there are unfavourable geological and mining situations, disrupting rhythmic development and an even front line. Often, a way to limit the impact of adverse geological and mining conditions is to reconstruct the front line on the runway and extract the remnant towards goafs or leave the remnant as a stabilizing pillar. Polish mining law permits mining in any direction and orders it to be stopped if the working front approaches the goafs to the distance less than 350 m. It also orders that further operation be carried out with the closing field, i.e. towards the deposit solid [2, 4].

The paper aimed at the evaluation of the seismic activity and efficiency of the rock-burst prevention related to five-year period of mining directed towards the goafs in #K mining field in Polkowice-Sieroszowice mine. The active preventive measures were assessed by percentage of the number and energy of blasting-induced tremors, the technological ones were evaluated with the number and energy of spontaneous tremors’ epicentres’ located in different zones related to an operational front and organizational measures-by means of 24-hour distribution of seismic activity. State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results.
2. Excavation towards mined-out areas

In the copper ore mines, from the launch of the first two mines i.e. Lubin and Polkowice to date, more than 100 km² of the deposit surface of various thicknesses, by different mining systems and different methods of managing the roof have been mined out. Consequently, geometrically diverse goaf areas as well as various supporting pillars between mined-out fields were created, the excavation of which is difficult.

The extracted areas and supporting pillars create a number of local places and zones of increased stress in the rock mass and the associated high rock burst hazards caused by local stress concentration. It may also be caused by incorrectly selected operating systems and their geometry. The increase in front speed is connected with an increase in the rock deformation speed, which results in a more fragile nature of damage and an increase in rock strength. The increase in rock strength is the reason that rock destruction occurs at higher critical stress, as a result of which the seismic threat increases. Choosing the proper way to control the roof also has a huge impact on the rock burst risk and depends largely on its behaviour over the mined-out space, determined in KGHM’s mines on the basis of the classification of roof rocks. From experience it is known that excessive concentration of works significantly increases rock burst hazard. This issue concerns the time necessary for relaxation of the rock mass and the proper coordination of works. An important factor increasing the state of danger is the restraining of exploitation, which may include remnants, supporting pillars, old goafs, front runways, deposit conditions, and surface development [2, 4].

Mining practice and scientific research show that seismic risk increases significantly when mining works are carried out in the vicinity of stopped mining edges and remnants. Most of the rock bursts in hard coal and copper ore mines occurred in the vicinity of the goafs. The line of old goafs delimits two centres differing in geomechanical properties with clearly different susceptibility to deformation. During exploitation it is inevitable to leave protective pillars and deposit remains. They become a place of stress concentration, which significantly affects the state of rock burst hazard. This threat occurs not only when picking up the left remnants. Such remnants pose also a threat to mining works carried out within its impact range [3, 4].

Cases of cutting fronts approaching goafs or yielding zones occur most often in situations when the need to reach for a deposit not originally intended for exploitation or not mined for various reasons, forces such direction of the front development. Exploitation towards goafs is limited to the yielding-cut works. The liquidation of workings usually takes place in the opposite direction sporadically in a direction perpendicular to the cutting direction. In the situations of front advancing towards adjacent goafs or susceptible zones, there are symptoms of an increase in rock mass pressure causing the destruction of roof rocks and, as a consequence, deterioration of roof stability, squeezing floor, stress relief and an increase in the level of seismic activity which is a potential threat of rock bursts [2, 3, 4].

In the KGHM’s mines, the cutting works towards goafs was necessary because of a roof collapse risk, rock burst hazard, mining issues, i.e. the existing geometry of goafs or previously made workings. The data indicated that as much as 65% rock bursts were connected with mining performed in the direction towards goafs or yielded places [4].

3. Research area description

The Polkowice-Sieroszowice mine is located in Lower Silesia in the Fore-Sudetic Monocline. The bedrock of the Monocline is made of Proterozoic metamorphic rocks such as crystalline shales, gneisses, granite-gneisses, phyllites and of Carboniferous sedimentary rocks. They are covered by Permian and Triassic sediments. The next stratigraphic unit that creates this monocline is a thick layer of Cenozoic sediments of sub-horizontal location. The rocks with copper mineralization originate from
the Permian period while the deposit rocks belong to the interface of the Rotliegend and Zechstein i.e. between the Lower and Upper Permian (figure 1).

The exploitation is carried out in three mining areas, namely Polkowice, Sieroszowice and Radwanice East. The surface of the Polkowice mining area is 75 km², the Sieroszowice one is of 96.99 km² and that of Radwanice East is 3.3 km². The Polkowice area lies in the central part of the Monocline and from the south-east near Radwanice East deposits, and from the north-west it borders directly with the Sieroszowice area, and from the north-east with the Rudna area, while from the south-east with the Lubin area and with the Głogow Gleboki area from the north-east.

The deposit is built from sulphides formed during the transgression and stabilization of the Zechstein Sea. It belongs to the stratoid type. The course of lithological boundaries is usually independent of the boundaries of the bed and the copper-bearing series. The prevailing type of ore in the Polkowice-Sieroszowice mine is shale carbonate ore, which accounts for about 90% of the ores. Regardless of the variability of the extent of mineralization in the vertical profile, the bottom of copper ore mining excavations are always gray sandstones of Rotliegend with a clay-carbon binder, while the direct and main roof is made of dolomite-limestone series of the Lower Zechstein. The main direction of dislocation in the Polkowice area is NW-SE and to a lesser extent W-E, which is represented by the Biedrzychowa fault zone. It runs through the centre of the mining area and divides it into two tectonic blocks. The northern part of the zone dropped from 20 to 70 m, is additionally cut by numerous faults in the NW-SE direction. Whereas the southern wing is hanging with faults, where the dominant direction is the direction NW-SE and NNW-SSE [1, 2].

Figure 1. Location of mines and geological structure of Legnica-Glogow Copper Belt, S-Sieroszowice mining area, P - Polkowice mining area, R-Rudna mining area, L-Lubin mining area
3.1. The #K mining field

The #K mining field belongs to the Polkowice mining area and is located in the northwest part of the region (figure 2). The analysis of seismic hazard was carried out for five-year long operational period. The field is situated within the dropped wing of the zone of the large fault called Biedrzychowa. The direction in which the deposit is located is similar to the NW-SE direction, but it may be varied in the vicinity of faults. Also, the dip angle of the bed generally ranges from 1 to 4º, however in the vicinity of the faults it is variable. The deposit is located at a depth of 850 m at the border of the mining area on the SE side of the protective pillars of the P-I and P-II shafts in Polkowice-Sieroszowice mine and the R-IV shaft in Rudna mine. The field of the planned exploitation was limited by the old goafs of the 1970s in the Biedrzychowa fault dropped wing and the goafs of another field from the 1970s and 1990s in the raised fault wing. The goafs of the 1990s of the old mining division were situated near the field in the Rudna mine.

Mining conditions of the exploitation are mainly determined by the physical and mechanical properties of rocks. The mined deposit in the #K field includes mainly carbonate rocks (dolomites and slates). Locally in the south-eastern part of the field, the roof layer of sandstones is also mineralized. The thickness of the deposit ranges from 1.0 m to about 4.0 m. Compressive strength of roof rocks changes from 84 MPa to 120 MPa and that of floor rocks accounts for 26 MPa-58 MPa. In the rock burst prevention used in the field attention was paid to cracking and raising up the compact sandstone layer in the floor at strong dynamic phenomena. For winning-blasting works additional floor shooting was introduced to increase their provocative effect. Due to the proximity of the Biedrzychowa fault zone, the rock mass is characterized by high tectonic involvement. There are faults in the direction of the run mainly NW-SE. The secondary direction of faults is NE-SW. Fault drop amplitudes range from about 3 m to 7 m. The tectonic involvement of the deposit is associated with a network of cracks with similar plane directions to the fault run. These cracks have a vertical fall. When assessing the rock mass conditions in the #K field, it should be emphasized that they do not differ from those in other, neighboring fields, where a deposit of similar thickness was chosen, an exploitation gate led on a compact layer of sandstone. The rock mass propensity for rock bursts is similar to the average level. Mining conditions are complicated by the occurrence of excavations and large-size pillars in front of the mining front in the plains.

![Figure 2](image-url) Location of #K mining field in Polkowice mining area (goafs are marked green)
4. Results and discussions
The seismic activity in the #K mining field was relatively high over the five-year period. So, it was necessary to apply a number of prevention activities such as technological, active and organizational-technical measures to mitigate and limit the seismic hazard.

4.1. Seismic activity
A seismic tremor is considered as a seismic event with energy of at least $1 \cdot 10^3$J whereas the energy of a high-energy tremors is of at least $1 \cdot 10^5$J. The seismic activity was low at the beginning and the ending of exploitation. There were 196 of tremors with the total energy of $6.45 \cdot 10^8$J. In the first year of exploitation there were the least number of tremors i.e. 10 and their total energy reached $1.18 \cdot 10^7$J (table 1, figure 3). This was due to the fact that the exploitation was not started until April that year. In the subsequent years, the 2nd and 3rd the number of tremors increased up to 65 and 82 respectively. The energy was increasing year by year and reached the biggest amount of $5.64 \cdot 10^8$J in the 3rd year. In the 4th and 5th years the energy decreased significantly. One may notice that in the period of the 2nd to the 4th year the adverse changes in the proportion of tremors with higher energies which may indicate the release of seismic energy through one-time dynamic phenomena with high energies, which significantly increases the risk of rock bursts. There were 35 high-energy tremors including 21 tremors of energy $10^3$J, 10 tremors of energy $10^4$J, 3 tremors of energy $10^5$J and 1 with energy $10^6$J. In the #K mining field, during the second and the third year the exploitation was conducted towards mined-out space.

| Years | Number of tremors | Energy of tremors, J | Energy for one tremor, J |
|-------|-------------------|----------------------|--------------------------|
| 1st   | 10                | $1.18 \cdot 10^7$   | $1.18 \cdot 10^6$        |
| 2nd   | 65                | $3.65 \cdot 10^7$   | $5.62 \cdot 10^6$        |
| 3rd   | 82                | $5.64 \cdot 10^8$   | $6.88 \cdot 10^6$        |
| 4th   | 18                | $1.50 \cdot 10^7$   | $8.33 \cdot 10^6$        |
| 5th   | 21                | $1.74 \cdot 10^7$   | $8.29 \cdot 10^6$        |
| 1st to 5th | 196               | $6.45 \cdot 10^8$   | $3.29 \cdot 10^6$        |

Figure 3. Seismic activity in #K mining field over five-year period.
During five years, four rock bursts occurred of which three were induced deliberately (provoked) with blasting and one was spontaneous. In the first year one rock burst occurred (spontaneous), in the third year two rock bursts occurred (two provoked), and in the fourth year there was one rock burst (provoked). These events took place at the depth of 850 metres. The most significant energy of $4.7 \times 10^8 J$ was released in the third year during the provoked rock burst and the least energy of $1.2 \times 10^7 J$ was emitted with the provoked in the fourth year when the exploitation front was decreased.

### 4.2. Rock burst prevention effectiveness

The rock burst prevention is incorporated into the exploitation technology and embraces the methods for recognition and reduction of the rock burst hazard as well as assessment of prevention effectiveness in combating the hazard. The effectiveness of the prevention may be connected with a change of the seismic hazard. Such an effectiveness enables one to find if preventive methods are used in a satisfactory way. The concurrent analysis of effectiveness and seismic activity makes it possible to evaluate the risk of a rock burst [2, 5]. The effectiveness of technological, organizational and active preventive methods was assessed.

#### 4.2.1. Technological methods of rock burst prevention.

To assess the effectiveness of technological methods during the exploitation conducted towards the goafs, the location of the epicentres of spontaneous was investigated (table 2). These epicentres can be located in the following three zones within the field of exploitation: A-in advance of the front (in the solid), B-within the working front, C-in the goafs. The aim of the technological preventive measures is to carry out the exploitation and manage the roof so that the energy can be emitted slowly and gradually. The most favourable location of the tremor epicentre is the goafs (C), while the least expected is the zone ahead of the front (A) since they can induce strain rock bursts. The number and energy of tremors in each zone was determined, which indicated the effectiveness of making the rock mass relaxed as a consequence of adequate technology. In the 1\(^{st}\) year, most tremors and energy occurred in the goaf zone (C). In the 2\(^{nd}\) year most tremors took place in the operational front, but the most amount of energy was in the goaf zone (C). In the 3\(^{rd}\) and 4\(^{th}\) years most tremors and their energy occurred within zone B. The occurrence of tremors in working front (B) is predictable to some extent, but they may induce the threat in the area. In the 5\(^{th}\) year most tremors took place in the operational front, but the most amount of energy was in the goaf zone (C). Over the years 1\(^{st}\)-5\(^{th}\), the percentage of the number of tremors in the solid (A) was 2\%, and that of energy was also 0.1\%, on the front (B) the percentage of the number of tremors was 60\% and that of energy was 28.2\%, while in the gobs (C) there was 37\% of tremors with the 71.7\% of energy. It can be claimed that the effectiveness of technological preventive measures was satisfactory, the location of tremors in relation to the operational front was favourable for reducing the seismic hazard.

| Zone       | A           | B           | C           |
|------------|-------------|-------------|-------------|
| Year       | 1\(^{st}\)  | 2\(^{nd}\)  | 3\(^{rd}\)  |
| Number of tremors/Percentage | 0           | 1/25\%      | 3/75\%      |
| Energy of tremors, J/Percentage | 0           | 5.3-10^5/5.7\% | 8.73-10^9/94.3\% |
| Year       | 2\(^{nd}\)  | 3\(^{rd}\)  | 4\(^{th}\)  |
| Number of tremors/Percentage | 1/2\%      | 25/60\%     | 16/38\%     |
| Energy of tremors, J/Percentage | 9.8-10^4/0.03\% | 9.71-10^8/2.75\% | 3.43-10^7/97.22\% |
| Year       | 3\(^{rd}\)  | 4\(^{th}\)  |           |
| Number of tremors/Percentage | 1/2\%      | 26/55\%     | 20/43\%     |
| Energy of tremors, J/Percentage | 1.4-10^4/0.5\% | 2.59-10^7/74.7\% | 8.61-10^6/24.8\% |
| Year       |             |             |           |
| Number of tremors/Percentage | 0           | 8/80\%      | 2/20\%      |
| Energy of tremors, J/Percentage | 0           | 4.38-10^5/94\% | 2.72-10^6/6\% |
4.2.2. Organizational-technical methods of rock burst prevention. It is possible to verify the length of the waiting time after group blasting with the use of the 24-hour distribution of seismic activity (figure 4). During the waiting time no miner is permitted to be at the place of blasting. A 2-hour waiting time after blasting operations was introduced in #K field in the period of the 1st-5th years. Most blasting works were performed between hours 5 and 7 in the morning and between 17 to 19 in the afternoon. The most favourable situation is when most energy is released during blasting works or in the waiting time, which makes working conditions safe. In the given period most energy of $4.88 \cdot 10^8$J (76%) was emitted between 5:00 do 7:00 am by 14 (7.1%) tremors and between 17:00 and 19:00 $1.15 \cdot 10^8$J (18%) by 4 (2%) tremors, which makes 94% of energy and 25.1% of tremors’ number. At other times, energy amount ranged from $10^5$J to $10^7$J. Therefore, it can be stated that the length of waiting time was adequate to successfully reduce the rock burst threat.

4.2.3. Active methods of rock burst prevention. The evaluation of the effectiveness of active preventive methods was calculated with the use of the percentage of the number and energy of tremors provoked by group blasting (table 3). Seismic tremor induction by blasting works and hence possible control of the time of their occurrence enables increasing the work safety. In the first year, the effectiveness of provocation in relation to tremors’ number was 70%, and with respect to the energy it amounted to 26%. In the second year, the effectiveness of provocation in relation to the number was 31%, and with respect to the energy it was only 3%. In the third and fourth year, the effectiveness related to the number of tremors was 39% and in relation to energy it reached 99% and 97 % respectively. In the fifth year the effectiveness related to number of tremors was 43% and to the energy 26%. During five
years, the average effectiveness for the number of tremors was 38% and for energy 49% (table 3). It can be concluded that the active preventive measures were highly effective in reducing the rock burst hazard. Moreover 75% of rock bursts were induced with the group blasting works.

Table 3. Effectiveness of group blasting works related to number and energy of provoked tremors over the 1st-5th years in the #K mining field.

| Years | Number of provoked tremors | Effectiveness (number of tremors) % | Energy of provoked tremors, J | Effectiveness (energy of tremors) % |
|-------|----------------------------|--------------------------------------|-------------------------------|--------------------------------------|
| 1st   | 7                         | 70                                   | $3.02 \times 10^6$             | 26                                   |
| 2nd   | 20                        | 31                                   | $1.05 \times 10^6$             | 3                                    |
| 3rd   | 32                        | 39                                   | $5.61 \times 10^8$             | 99                                   |
| 4th   | 7                         | 39                                   | $1.45 \times 10^7$             | 97                                   |
| 5th   | 9                         | 43                                   | $4.58 \times 10^8$             | 26                                   |
| 1st-5th | 75                     | 38                                   | $3.13 \times 10^8$             | 49                                   |

5. Conclusions
In #K mining field the efficiency of technological, active and technical-organizational preventive measures was satisfactory over the period of five years when the exploitation was conducted towards goafs and yielded areas. In KGHM’s mines, conducting the cutting works towards goafs has been forced by: a roof collapse hazard, occurrence of rock bursts, mining situation, i.e. the existing layout of goafs or corridor headings made earlier. At the time of designing the exploitation, it was never assumed that it would be directed towards goafs or previously yielded zones. The data shown that as much of rock bursts took place when conducting works towards goafs or yielded areas; and the fact of provoking the seismic event on the one hand shows a kind of preparation of the rock mass for the occurrence of such a process, on the other hand it may indicate a successful application of rock burst prevention. The hitherto advancement of exploitation in individual mines and the scope of mining works planned for the coming years allows to put forward the thesis that the problem of conducting exploitation towards goafs, will gradually increase, and the main reason for this is the level of depletion of the deposit in mines.

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