Passive Seismic Tomography as a Tool of Rock Burst Hazard Prognosis in Copper Ore Mine in Poland

Anna Barbara Gogolewska 1, Daria Smolak 1

1 Wroclaw University of Science and Technology, Poland

ana.gogolewska@pwr.edu.pl

Abstract. In Poland, underground mines of copper ores, which belong to KGHM Polish Copper JSC, have been struggling with seismic dynamic events such as tremors and rock bursts since almost the first years of exploitation i.e. the 70s of the twentieth century. Mining activities infringe the original stress balance and make the rock mass accumulate energy and then release it, which triggers seismic hazard even far away from a tremor epicentre. Therefore, prediction of the position, time and energy of tremors plays a significant role in mining operation especially in work safety. For this purpose, many observation methods including seismology, seismic, geotechnical-geological monitoring, are used; unfortunately, most of them help describe the state of the rock mass after but not prior to the occurrence of the seismic phenomena. Only passive seismic tomography is promising since it can be used to forecast, to some extent, the location of places of seismic energy excessive accumulation. In this method, on the basis of seismic events recorded in a given period, zones of high and low seismic wave velocity are determined (calculated), which in the near future may pose areas of increased seismic activity. The phenomenon of the increase of seismic longitudinal wave velocity with the increase of stress in rocks makes the ground of tomography calculations. The prime purpose of the paper is to assess passive seismic tomography as a means for forecasting and evaluation of seismic and rock burst hazard. To accomplish this, the analysis of seismic activity and archival seismic tomography results (seismic wave velocity zones and seismic anomaly zones) with reference to seismic phenomena, their energy, number and location were carried out. On the basis of obtained the results, the effectiveness of seismic hazard forecast with the use of passive seismic tomography was assessed. The research was carried out for one mining division of the Polkowice-Sieroszowice mine and covered ten years. This division was selected due to its high seismic activity and the permanent use of the passive seismic tomography to assess the seismic risk. Linear correlation and determination coefficients between seismic activity characteristics and seismic anomaly as well as longitudinal wave velocity were calculated. It was found that in the study area the effectiveness of passive seismic tomography in forecasting the seismic hazard is relatively satisfying since about half of the tremors were located within zones of high seismic activity (substantial velocity of P-waves and seismic positive anomalies).

1. Introduction

Three deep copper ore mines (Lubin, Rudna and Polkowice-Sieroszowice), which belong to the KGHM Polish Copper JSC, have been excavating copper and silver ore deposit for about fifty years. Since the very beginning, mining operations have been accompanied by tremors and their effects in workings called rock bursts which pose the most dangerous and unpredictable underground threat.
These seismic dynamic events are of the same origin i.e. they are caused by the rock mass instability. Tremors triggered by excavation are called mining-induced ones. Seismic phenomena including rock bursts can be mining-induced (called spontaneous) which means that they are uncontrolled or blasting-induced (called provoked) which means that they are caused purposely with winning-blasting works to release energy and hence to reduce the stress increased within the rock mass.

The first rock burst occurred in 1972 in the Polkowice-Sieroszowice mine and since then a lot of prevention measures have been developed to recognize, mitigate, reduce and monitor the rock burst and seismic hazards. Recognition of rock burst hazard plays the crucial role in prevention. Seismology, seismic methods, seismic acoustics are implemented to assess and monitor seismic activity of the rock mass but they can only monitor the situation after seismic events. High-energy spontaneous tremors are the most threatening as they cannot be controlled. Therefore, forecasting the areas where spontaneous tremors are probable to occur plays a crucial role in work safety providing and should give not only the place but also the time and energy of a tremor. So far, solely one method i.e. passive seismic tomography has been able to forecast a spontaneous tremor but merely its location. So far, only one method i.e. passive seismic tomography has been able to forecast merely the location of a spontaneous tremor. This method predicts, to a certain extent the location of energy accumulation zones, which in the near future may be probable areas of increased seismic activity. The zones are defined on the basis of seismic events occurring in a given period prior to mining operations. In these zones, increased accumulation of energy in the rock mass hence potentially higher seismic activity is manifested by increased velocity of a longitudinal seismic wave and high positive seismic anomaly.

The paper attempts to verify the passive seismic tomography as a method to forecast and assess the rock burst hazard and seismic activity. Therefore, the geological-mining conditions, seismic activity and archival tomography results were investigated. The seismic wave velocity and anomaly, obtained by tomographic calculations, were analysed in relation to the location, number and energy of spontaneous seismic dynamic events including rock bursts. The G-23 mining division of the Polkowice-Sieroszowice mine was studied due to its high seismic activity and the big number of rock bursts; for example, there were 23 rock bursts in years 2009-2016. The calculation concerned the 2007-2016 years’ period. Moreover, seismic tomography calculations have been regularly performed there every three months.

A lot of spontaneous seismic dynamic events were found within the zones of high seismic anomaly and wave velocity. However, some high energy tremors were noticed in zones of a very low wave velocity and negative seismic anomalies, which may indicate the low usefulness of the tomography for predicting the rock burst hazard.

2. Study area and methodology depiction
The Polkowice-Sieroszowice mine is situated within the Legnica-Glogow Copper District, in the northern part of Lower Silesia located in the south-west Poland. The copper ore deposit is exploited by the KGHM Polish Copper JSC by means of three deep mines (Rudna, Lubin and Polkowice-Sieroszowice) within the following mining areas: Lubin-Malomice, Polkowice, Sieroszowice, Radwanice-East and Rudna. Nowadays works are being performed to open Glogow-Gleboki Przemyslowy mining area and to recognize Radwanice and Gaworzyce deposits. The aforementioned mining fields are presented in figure 1. The Polkowice-Sieroszowice mine started in 1996 when two separate mining plants i.e. Polkowice and Sieroszowice were joined. In 1963 the Polkowice mine was established while the Sieroszowice mine, in 1980. The Polkowice-Sieroszowice mine possesses three mining areas i.e. Polkowice, Sieroszowice and Radwanice-East [1, 2, 3].

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2.1. G-23 mining division
The G-23 mining division is situated in the north west part of the Polkowice mining area (figure 1) within GG-3 exploitation region. In 2016 there were 6 mining panels (A, C, D, G, H and I). In 2017 the region was renamed into PO-1 and was divided into 2 following panels: PO-1/1 in the north (former A, C and G panels) and PO-1/2 in the south (former D, H and I panels). The copper ore deposit was opened by means of two shafts and drifts. The ore deposit is extracted with the use of the one-stage room-and-pillar mining system with roof self-deflection (J-UG-PS). This method is dedicated to mine pseudo-seam deposits with the thickness of 4.5 to 6 metres and inclination equal or less than 8º. Roof bolting makes a support system. The length of an exploitation front reaches at least 200 metres. If the thickness of a deposit is less than 4.5 metres, mine workings are to be built near to a roof. The pillars and the solid edge are made to yield. Hence, the pillars yield and work under the non-destructive condition; they are called technological [4]. The highest category of rock-burst hazard was implied for the G-23 division. The ore deposit is cut into rooms and pillars with concurrent separation of technological pillars with 5-9 metres by 6-16 metres dimension. The pillar longer side is normal to the front line and secures the roof of empty exploited area. The cut of mine workings are to be up to 6 metres wide and up to 4.5 metres high according to the deposit thickness. The group blasting is used to win the deposit [5].

![Figure 1. Location of mining fields within Legnica-Glogow Copper District.](image)

2.2. Seismic tomography
Seismic activity induced by mining operations is recorded by mine seismological network. On the basis of registered parameters, it is possible to calculate tremor epicentre position and energy released by the rock mass as well as the structure and strength parameters of rocks with the use of seismic waves propagating through the rock mass. The seismic tomography examines an object structure without damaging it and relies on calculating the seismic wave properties and their distribution model within the medium. Most often the travel time, velocity and amplitude of a longitudinal wave are measured and calculated to investigate the object interior structure [6]. In mines, both the active and
passive tomography can be implemented. Mechanical impact or explosives are used in active observations to cause vibrations while passive examinations employs mining-induced tremors noted with mine seismological network. When the stress in a rock mass increases P-wave velocity whose direction is parallel to the direction of stress also increases, which may be caused by closing the pores in rocks. Therefore, observations of the velocity of seismic waves, make it is possible to predict changes of stress distribution and in consequence the seismic hazard. Additionally, tomographic calculations relocate tremors, which enables to determine their location more precisely avoiding the in-situ measurements [7]. The epicentres of high-energy tremors are often registered in zones of significant velocity of P wave and the high gradient of velocity while the zones with low seismic activity are connected with the low P wave velocity [8]. The velocity zones should be investigated regularly since the strain and stress fields changes rapidly especially in excavation areas, and the development of operational fronts should be taken into account [7]. The changes of the wave velocity and seismic anomaly fields, make it possible to find the seismic hazard zones and to determine their spatial distribution in time [2].

2.3. Investigation methodology
Analysis of the passive seismic tomography as a tool for prognosis of rock burst hazard was connected with the simultaneous investigation of the archival tomographic results and seismic activity. The prognosis which means the prediction of location, time and energy of spontaneous tremors occurrence was the most important issue to analyse. The pertinence of stress areas location within the rock mass obtained with the use of seismic wave velocity and seismic anomaly calculated by means of seismic tomography was assessed. The archival tomographic documentation received from the Mine Rock Burst Department was employed to depict areas of the high and low wave velocity and seismic anomaly. The archival tomographic calculations done for a given time period were related to tremors that occurred prior to the calculation period, usually within two or three previous months. When images of wave velocity fields are observed in subsequent time windows, the location of hazardous zones can be monitored. The tomography may enable one to predict a potential seismic risk within a given time and space, with the use of empirical data. The areas of elevated wave velocity compared to the average velocity are considered as the places of significantly stressed rock mass while the areas of high velocity gradient are the zones of highly probable emission of elastic energy [8].

The agreement of the passive tomography results with the real conditions in the mining workings was verified with regard to the location of the spontaneous tremors that occurred over the period (after tomographic tests) for which the prediction was carried out. The spontaneous tremors, which took place within 8 weeks after tomographic calculations, were placed on the map. The position of the maximum, minimum and average velocities and seismic anomalies were given on contours maps. The tomographic results enabled one to find and verify the forecast location of the areas of the potentially high seismic threat. In the years 2007-2016, 56 passive tomographic tests were completed. The location (coordinates), number and energy of spontaneous tremors were analysed in relation to the location of seismic hazard zones predicted (calculated) with seismic tomography. High and low velocity zones of longitudinal wave as well as positive and negative seismic anomalies were investigated and described.

3. Results and discussions
The method of passive seismic tomography is mainly used in underground mines characterized by high seismic activity. To determine the effectiveness of using the results of this method in predicting a seismic hazard, it is necessary to investigate the seismic activity especially that connected with spontaneous tremors. All seismic tremors occurring at that time, the energy of which was greater than or equal to $10^3\text{J}$ (including tremors for which the coordinates were not known) were taken into account.
3.1. Seismic activity in G-23 division
The seismic event with energy of at least $1 \cdot 10^3$ J is considered a tremor while the energy of a high-energy tremors reaches at least $1 \cdot 10^5$ J. Characteristics of seismic activity focused on the number of tremors including the high-energy ones, on the number of spontaneous tremors, on the WZSE3 seismic hazard index for spontaneous tremors, and on the number of rock bursts.

In years 2007-2016, there were 5777 tremors including 782 high-energy ones (14%) and 3939 (68%) spontaneous tremors (table 1, figure 2, figure 3). In 2015 the most tremors (946) and the most high-energy tremors occurred (154). The least tremors (414) took place in 2010 and the least number of high-energy ones (38) were noted in 2011. The WZSE3 seismic hazard index changed from 162 (year 2011) to 313 (year 2015), on average 211; this index increases with total energy. There were 32 rock bursts including 11 spontaneous ones (34%) (figure 4). Most (55%) spontaneous rock bursts were caused by tremors with energy of $10^6$ J. One of them was triggered by a tremor with energy of $10^3$ J and 4 of them were connected with energy of $10^7$ J (figure 5).

Table 1. Seismic activity in the G-23 mining division in years 2007-2016.

| Years | Number of tremors | Number of high energy tremors | Percentage of high-energy tremors, % | Number of spontaneous tremors | Percentage of spontaneous tremors, % | WZSE3 |
|-------|-------------------|------------------------------|--------------------------------------|------------------------------|--------------------------------------|-------|
| 2007  | 500               | 86                           | 17                                   | 312                          | 62                                   | 170   |
| 2008  | 484               | 90                           | 19                                   | 333                          | 69                                   | 194   |
| 2009  | 444               | 90                           | 20                                   | 298                          | 67                                   | 200   |
| 2010  | 414               | 42                           | 10                                   | 269                          | 65                                   | 170   |
| 2011  | 431               | 38                           | 9                                    | 324                          | 75                                   | 162   |
| 2012  | 493               | 61                           | 12                                   | 334                          | 68                                   | 179   |
| 2013  | 657               | 69                           | 11                                   | 493                          | 75                                   | 252   |
| 2014  | 750               | 59                           | 8                                    | 575                          | 77                                   | 274   |
| 2015  | 946               | 154                          | 16                                   | 605                          | 74                                   | 313   |
| 2016  | 658               | 93                           | 14                                   | 396                          | 60                                   | 219   |
| 2007-2016 | 5777             | 782                          | 14                                   | 3939                         | 68                                   | 2108  |

Figure 2. Number of low-energy and high-energy tremors in the G-23 mining division in years 2007-2016.
The seismic activity in the G-23 division was high over the whole period of 2007-2016 years. Therefore, it was necessary to apply a number of methods to recognize and monitor the rock burst hazard and seismicity of the rock mass. The prime method of monitoring was mine seismology which obtains the information about each tremor including coordinates of the tremor epicentre and the energy of each tremor. Moreover, the passive seismic tomography was implemented to monitor the state of the rock mass.

Figure 3. Number of provoked and spontaneous tremors in the G-23 mining division in years 2007-2016.

Figure 4. Number of rock bursts in the G-23 mining division in years 2007-2016.
3.2. Prognosis of seismic activity with the use of passive tomography

To verify the passive seismic tomography as a tool for predicting the seismic hazard, an analysis of its archival results in relation to seismic activity was carried out for the G-23 division over the 2007-2016 period. The key term here is the word prognosis i.e. prediction of the place, time and energy of a seismic event. Therefore, the analysis primarily refers to the three factors. The spatial distribution of seismic wave velocity and seismic anomalies calculated with the seismic passive tomography was referred to location of tremors. The number of tremors, which occurred within the zones of high/low wave velocity and seismic anomaly may indicate the accuracy of prognosis of the stress distribution within the rock mass. The increase in the seismic wave velocity is associated with an increase in the stress and strain of the rock mass and hence the potential seismic hazard. The analysis covered 56 tomographic results including 384 wave velocity zones, 384 seismic anomaly zones and 5777 tremors. Table 2 presents the analysis results including the number of spontaneous tremors which was located within the division by coordinates, number of spontaneous tremors located in high wave velocity zones predicted with seismic tomography and effectiveness of tremor location prognosis.

In 2007 17% of tremors occurred in the zones of the increased wave velocity, the rest tremors took place in the close vicinity of these zones. In addition, there was a rock burst but not associated with any of these zones. In 2008, 24% of tremors occurred in high-velocity zones, the others occurred in close proximity to these zones. Outside the high-velocity zones, there was a tremor with energy of the $10^7$J order, which caused a rock burst. In addition, in low-velocity zones where there should be no seismic activity, 15 tremors with a total energy of $5.1 \cdot 10^5$J took place.

The year 2009 was marked by increased seismic activity; 42 tremors occurred on and ahead of the mining front. Two strong seismic tremors with energy of the order of $10^7$J occurred outside of the determined high-velocity zones. In September in 2019, when the highest seismic activity was observed, prediction of the tremor location was very effective and amounted to 81%. There were 37 tremors in low-velocity zones, where the anomaly reached even -15%, and the highest energy did not exceed the order of $10^5$J.

In 2010, 48% of spontaneous tremors occurred in the calculated zones of the high wave velocity. The total energy of these tremors was of the order of $10^5$J, $10^6$J, and $10^7$J. No tremors occurred in low-velocity zones. In 2011 the tremor location prediction was very good as 91% of tremors appeared in high-velocity zones. During this year, only one tremor occurred in a low-velocity zone. In 2012, the effectiveness of predicting the location of seismic events reached 72%. No tremors were detected in
low-velocity zones. In 2013, tremors which took place in the high-velocity zones represented 72%. There was a strong energy tremor of $10^6$J resulting in a rock burst in one of these zones. In addition, three tremors with a total energy of $1.9 \cdot 10^5$J were recorded in zones of low seismic activity, i.e. of low-velocity and low-seismic anomaly.

In 2014, seven zones of the high wave velocity were determined. In May, a tremor of $9.6 \cdot 10^4$J which caused a rock burst was recorded in a high-velocity zone. In August, however, the $2.1 \cdot 10^4$J tremor resulting in a rock burst was located in a low-velocity zone; there were 22 other tremors, the total energy of which reached $1.5 \cdot 10^5$J. The effectiveness of the tremor location prediction i.e. the occurrence of tremors in predicted high-velocity zones, acquired 64%.

In 2015, 58% of tremors occurred in high-velocity zones. Moreover, the tremor of $2.8 \cdot 10^4$J energy resulting in the rock burst, occurred in one of these zones. On the other hand, two tremors with the energy of $10^5$J took place outside these zones. In addition, six tremors occurred in zones with predicted the lowest seismic activity. In 2016, tremors located in determined high-velocity zones constituted 63%. A tremor of energy of $4.6 \cdot 10^4$J which caused a rock burst occurred in one of these zones. In two zones of low seismic wave velocity five tremors with a total energy of $4.2 \cdot 10^5$J took place.

It can be concluded that in the G-23 division the occurrence of tremors in the prognosed zones of elevated seismic wave velocities was quite diverse (table 2). The lowest percentage of tremors in these zones i.e. the lowest effectiveness of tremor location prognosis was observed in the first two years (2007 and 2008), 17% and 24% respectively. In other years, this effectiveness was not lower than 48% and in three cases exceeded 70%. The most effective tremor location prognosis reached 91% in 2011. Over the period of 2007-2016, the location of 56% of tremors was successfully predicted by means of passive seismic tomography.

| Year | Number of spontaneous tremors | Number of spontaneous tremors in high velocity zones | Effectiveness of tremor location prognosis |
|------|-------------------------------|-----------------------------------------------|------------------------------------------|
| 2007 | 360                           | 62                                            | 17%                                      |
| 2008 | 272                           | 64                                            | 24%                                      |
| 2009 | 261                           | 136                                           | 52%                                      |
| 2010 | 296                           | 141                                           | 48%                                      |
| 2011 | 197                           | 179                                           | 91%                                      |
| 2012 | 293                           | 212                                           | 72%                                      |
| 2013 | 432                           | 313                                           | 72%                                      |
| 2014 | 513                           | 329                                           | 64%                                      |
| 2015 | 524                           | 304                                           | 58%                                      |
| 2016 | 357                           | 226                                           | 63%                                      |
| Total| 3505                          | 1966                                          | 56%                                      |

3.3. Number and energy of spontaneous tremors, wave velocity and seismic anomaly

As part of the analysis, it was checked whether there is a relationship between the number of tremors and their energy and the seismic anomaly and the velocity of the seismic wave in the areas of high seismic hazard determined with the passive tomography. Correlation coefficients were calculated, too.
Number of tremors vs maximum velocity of seismic waves in predicted high-velocity zones. Maximum velocities of seismic waves in zones determined with the use of seismic tomography were taken into account. The relationship between the number of tremors appearing in the prognosed high-velocity zones and these maximum velocities was analysed. The most tremors were connected with seismic wave velocity of 6800 m/s. Maximum velocities of 6100-6800 m/s were obtained in calculations done for the period of 2007-2011 years. In years 2012-2016, maximum wave velocities were not higher than 6000 m/s, which may have happened due to gradual deterioration of roof conditions, exploitation in the faulted zone or disturbances in the continuity of roof layers. In the aforementioned years, the most seismic events were recorded in high-velocity zones where the maximum velocity reached 5800 m/s and 5700 m/s. In low-velocity zones with velocity of 4600-5500 m/s the number of tremors was significantly smaller. The linear correlation coefficient was 0.35, which indicated the relatively significant number of tremors and velocity of seismic waves in prognosed zones of high-velocity. Therefore, it cannot be unequivocally determined whether more tremors were associated with higher seismic wave velocity i.e. with increased strain accumulated in rock mass.

Number of tremors vs seismic anomaly in predicted high-velocity zones. Most tremors occurred for an anomaly greater than or equal to 10%, so in places where the wave velocity was 10% higher than the average velocity in a given area. The majority of tremors were connected with the anomaly of 13% and 11%. The occurrence of tremors in zones with a large negative anomaly was unfavourable for the effectiveness of the tremor location prognosis. The relatively significant number of tremors occurred in a zone of -9% seismic anomaly. Negative seismic anomalies are characteristic of the prognosed low-velocity zones where tremors and rock bursts should not appear. The linear correlation coefficient reached 0.47, which indicated the directly proportional relationship between the number of tremors and seismic anomaly. In the zones of positive seismic anomalies 95% of tremors occurred.

Total energy of tremors vs maximum velocity of seismic waves in predicted high-velocity zones. The largest total energy of $1.9 \times 10^9$ J occurred at a wave velocity of 5800 m/s. Large energy over $1 \times 10^9$ J was also observed for the wave velocity range 5500-6000 m/s and for the velocity of 6800 m/s. The least energy was connected with the velocity of 6200 m/s. Some large total energy, however, resulted from single tremors of the energy order of $10^9$ J or $10^7$ J. The linear correlation coefficient was 0.16, which indicated a very weak directly proportional relationship between the tremor energy and wave velocity in the prognosed high-velocity zones.

Total energy of tremors vs seismic anomaly in predicted high-velocity zones. The biggest total energy of $10^9$ J order was observed for seismic anomaly of 13%, 11% and 8%. The smallest total energy was connected with the seismic anomaly of -20%. The higher total energy was connected with a positive anomaly. Unfortunately, some negative anomalies were connected with the high energy of the $10^7$ J order. Such situation was not related with the high number of tremors but with a single tremors of a significant energy. The linear correlation coefficient was 0.45 and indicated directly proportional relationship between the tremor energy and seismic anomaly in the predicted high-velocity zones.

4. Conclusions

It was shown that the passive seismic tomography was successfully applied to predict the place of a tremor occurrence over the ten-year-period. The prognosis effectiveness was good, however not satisfactory enough. Fifty-six percent of tremors appeared in zones in which high seismic activity was predicted by means of tomographic calculations. The prognosed seismic activity was connected with the velocity of longitudinal waves, which increased with increasing stress of the rock mass hence with increasing potential energy. A lot of tremors occurred close to high-velocity zones, determined with tomography. Moreover, most rock bursts took place in high-velocity zones. However, many tremors
and the substantial tremor energy appeared in zones of low velocity and negative seismic anomaly where seismic activity had to be very low. There were also several rock bursts, which was unfavourable for the effectiveness of tremor location prognosis. The smallest annual effectiveness of the tremor location prognosis was 14%, the biggest one reached 91% and, in most years, the effectiveness was not lower than 48%. The weak directly proportional relationship was found between the number of tremors and the maximum wave velocity and also between the energy of tremors and the maximum wave velocity in the prognosed high-velocity zones. The directly proportional relationship between the number and energy of tremors and the seismic anomaly in the predicted zones of high velocity was determined. Nearly all of tremors occurred in the zones of positive seismic anomaly.

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