Seismic activity of hard coal longwall mining in protective shaft pillar near closed room and pillar panel

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Abstract. Monitoring of seismic activity during mining in the Upper Silesian Coal Basin is a part of rockburst prevention system. System is composed from two parts – seismological (SL) and seismoacoustic (SA) monitoring. Evaluation of data from both systems allows describing stress deformation process during mining and evaluation of rockburst mitigation techniques effectiveness. Described longwall was mining in a protective pillar after two trial room and pillar (R&P) testing panels were completed. Evaluation of seismic activity was carried out by special software tool which allows simulating daily advance of mining and registered seismic activity. Different mining stages were identified for evaluation of seismic activity (e.g. weekly and daily summary graph of seismic activity, Benioff graph, event rate graph, energy vs time graph etc.). Evaluation of seismic activity provides many interesting results, mainly in the area of longwall panel termination when one pillar of the R&P trial was impacted by the longwall. This work presents seismic activity analysis, detailed site conditions and implemented active rockburst measures and its effectiveness. Analysis of seismic activity allows to formulate conclusions for longwall mining operations and evaluation of seismic activity in unfavourable geomechanical conditions within the area of protective shaft pillar border.

1. Introduction
Coal mining is still one of the most dangerous branches of all working environments. Seismic events induced by coal mining has been a common occurrence in the Czech Republic [1] as well as in Poland e.g. [2] because mining regions in the Czech Republic and Poland represent one coal basin (Upper Silesian Coal Basin – USCB). One of the most useful ways to observe or predict induced seismicity within the rock mass in which mining operations are situated is to monitor the seismic activity in the demarcated area [3]. It is essential to identify part of the rock mass where there is a large number of high-energy tremors, or the part with a specific local accumulation of low- and high-energy seismic events [4]. Mining of previously untouched pillars (protective shaft pillars, protective crosscut pillars, etc.) is dangerous due to complicated stress field development in protective pillars due to long term mining in their vicinity. With the knowledge of the local conditions and to ensure the safety of the workers and mining technology, a seismic monitoring system was suggested as one of the main preventive methods. Seismic activity due to longwall mining in the border of protective shaft pillar, where R&P mining method was tested in the last two years, is the main goal of this paper. Induced seismicity was evaluated including seismic activity due to longwall impact of pillars developed by R&P method by advancing the longwall face. An explanation of the used mining terms which could be not known in rock mechanics can be found in e.g. [5].
2. Geological and geomechanical conditions
The mining area was situated in one of the mining operations in the southern part of the USCB. For the recent mining panel, coal seam 30 was chosen. This seam is categorised as a seam without the potential for rockburst occurrences. The seam’s thickness varies from about 160–220 cm and is situated at a depth from about 800-870 m below the surface. The seam dips at an angle of 8° to the North-East.

The roof rocks are composed of sandstone and siltstone layers. From the bottom to the top, the roof rocks are as follows: On top of the coal seam 30 is a thick layer of siltstone with small layers of grainy sandstones. The formation continues with fine-grain and coarse-grain sandstone layers and finally a layer of siltstone, which represents the nearest sublayer of the coal seam 29. Underneath the seam 29, there is a small unmarked seam.

Bedrocks below the seam 30 consist of the siltstone layer underlined by the coal seam 31. Thereafter, the formation continues with the layer of siltstone and the coal seam 32 below. Further down is the root siltstone layer (see figure 1).

Stratigraphic studies of the area proved the existing thrust fault near the mining area, which was confirmed when driving the roadway in the seam 30. The throw of the fault was 5 m. The fault line lies in the NW and divides into several small overlaps further to the north. The fault is close to horizontal at an angle of 20°.

Geomechanically the area has been studied in the past by several geological drillings. The cores were inspected and geomechanically evaluated; the results brought an understanding of the rock strength properties with information about lumpiness and the number and angle of discontinuities in the drilled core [6]. The median of calculated uniaxial compressive strength is 123.8 MPa for the sandstone, 90.3 MPa for siltstone, 63.3 MPa for root siltstone and 21.9 MPa for the coal seam.

3. Seismic monitoring
3.1. Seismological monitoring
As one of the first of studied methods, we used a seismological polygon monitoring system. It is a regional network of 10 seismic stations equipped with triaxial medium motion seismometers located in the boreholes from the surface or in the active mines [8], see figure 2. These station positions were designed around the active and historically inactive mines to provide a continuous data stream of changing SL activity through time. Its purpose is to provide nominal basic data acquisition and evaluation of SL activity in the whole region of the southern part of the USCB.
The micro-seismological monitoring system was designed for the purpose of refining the localization accuracy. To precisely triangulate the events in this small area, the local mine network of 6 uniaxial seismic stations was extended by another 6 new stations around the R&P trial mining panels (see figure 3). In the final stage, the network was made of 11 stations equipped with uniaxial, low-frequency and low-periodical vertical seismographs. This network was used to gather important data of low-energy events that were supposed to be present during the longwall mining.

![Figure 2. Map of seismic network in south part of the USCB.](image)

3.2. Seismoacoustic monitoring

During the preparation stage another SL method was also considered to be useful for monitoring. This method was developed for purposes of longwall mining system to gather data for geomechanical and statistical evaluation of longwall mining panels and its influence on brittle deformation of coal mass in front of the advancing longwall. The method uses 4 acoustic geophones installed in boreholes in coal seam and 1 is installed in roof rocks. In the coal seam, first pair of geophones must be installed at a maximal distance of 50 m in front of the excavated area from each gateway. The last pair of geophones must be installed at the maximal distance from mine workings, but not more than 100 m away. The roof rock geophone can be installed no further than the last pair of geophones. As the longwall advances towards the geophones the pairs of geophones must be moved forward.

![Figure 3. Schematic map of study area.](image)
In this case the SA method was used in different manner. The mining operation advanced onward from the base and therefore it was not possible to monitor the SA events in foreground. This method was used to monitor the geomechanical movements and activity under the stabilizing geomechanical conditions. So it also contributed to monitor and localize the smallest seismic events present inside of mining panel. Thanks to this fact, this system monitored the rock mass around the escape roads for the workers. This method was also helpful as a mean of early warning system for the mine personnel.

To gather as much data as possible, the SA method was also used to monitor the remnant pillar.

4. Results and Discussion

Different mining stages were monitored using the standard tools for evaluation of seismic activity (e.g. weekly and daily lines of summary graph of seismic activity, Benioff graph, event rate graph, energy vs time graph etc.).

Evaluation of seismic activity was also carried out using the special software tool which allows simulating daily advance of mining and registered seismic activity. It allows to perform a detailed spatio-temporal analysis of seismic events occurrence. It is available for selected date as well as for various time periods around selected date. After defining the visualisation parameters, the automated display of individual seismic situations in selected over the time span. The graphic information of the map composition complements the graph of dependency of seismic (SL/SA) activity in the area during the daily progress of the longwall mining. The combination of the map view and the corresponding graph allows simple detection of the non-homogenous seismicity in the area. Weekly and daily summary graphs and seismic events localisation maps were selected for presentation.

4.1. Seismological monitoring

Registered SL activity during longwall advance is depicted in figure 4 and the map of registered seismic events during the particular phase of mining is shown in figure 5. In the graph, three phases (A, B and C) can be identified, that are characterised by the most significant weekly energy variations.

![Figure 4. Summary graph of longwall advance, SL activity, SA activity and Benioff graph of registered SL activity.](image)

**Phase A (until 2018-10-31)**

The first phase A is distinguished by a rapid increase in seismic activity. This case is clearly connected with the initialization phase of the longwall run (square goaf position – longwall advance equal to the width) based on the similar shape of the two curves (daily and weekly seismic activity). During this initial stage of excavation the longwall was situated in a location where additional stress was generated from earlier longwalls in seams in the overburden.

The localization of events was predominantly in the area of additional stresses from seam 30 goaf edge and seam edges in the overburden. Smaller amount of seismic events were localised in the wider surroundings (protective pillar, areas of mined seams towards to the NE, more distant from the longwall...
face). The seismic events with energy of $10^5$ J were located both in the area of longwall face and in the area of mined seams on the NE of the mining panel. In total, number of 533 registered events were detected with prevalence of $10^1$ and $10^2$ J events. There was also a significant number of $10^3$ J events (10%), $10^4$ J events (5%) and $10^5$ J events (3 events). The total registered released seismic energy was $2.08 \times 10^6$ J in the Phase A.

**Phase B (2018-11-01 to 2019-01-31)**

During the next phase B, when the goaf of the longwall started to connect with the goaf of the previously mined longwall, the seismic activity began to decrease. During this phase, weekly variations in seismic activity do not respond as sensitively to the longwall face advance as in the phase A. The maximum seismic activity was caused by the occurrence of high-energetic tremors ($10^5$ J) in the goaf area of the longwall. Fracturing of high overburden was observed in this phase.

The localization of events was predominantly concentrated in the area of additional stresses from the seam 30 goaf edge and seam edges in the overburden. Smaller amount of seismic events were localised to the wider surroundings (protective pillar and the areas of mined seams on the NE). Seismic events with energy of $10^5$ J were located in the goaf part of mining panel. The total number of 219 registered seismic events decreased by less than half compared to the phase A. There is a prevalence of $10^1$ and $10^2$ J events with the occurrence of a significantly smaller number of $10^3$ J events (5%), $10^4$ J events (1 event) and $10^5$ J events (1 event). The total registered released seismic energy was $7.69 \times 10^5$ J in the Phase B, what was one order of magnitude lower than in the previous phase A.

![Figure 5. Localisation of registered SL events (Phase A - left; Phase B - right).](image)
10^6 J in the phase C. At this stage of mining, a similar amount of registered seismic energy was released as in the phase A, but through events of significantly smaller energies.

From the Benioff graph of registered seismic activity (figure 4) we can select the sub-phase C1 within phase C (figure 5). It began from 9 May 2019 after 10^6 J seismic events were recorded on 8 May 2019 and continued to the end excavation. This event was localised in goaf area on the border between the goaf of explored longwall and previous longwall in NE direction. Seismic activity increased rapidly after that. In sub-phase C1 10^1 J events (82%), 10^2 J events (17%) and 10^3 J events (3 events) were recorded. Total released energy was 6.99 10^4 J in sub-phase C1. Sub-phase C1 represents 44 % of all recorded seismic events in phase C.

Figure 6. Localisation of registered SL events (Phase C - left; sub-phase C1 - right).

According to the above mentioned analysis of seismic activity during longwall mining we can formulate following partial results:

- Seismic events are recorded mainly from areas of additional stress from previous mining in the coal seam and seams mined in the overburden.
- Seismic activity is sensitive to longwall advance mainly in the phase A of longwall advance (up to square goaf position) and in the area of longwall panel termination in phase C (occurrence of remnant coal pillars).
- Seismic activity in period when longwall reached square goaf position contain significant amount of high energetic seismic events (15 % events up to 10^3 J according to the local rockburst rules).
- Seismic activity rapidly decreases in phase B after exceeding of square goaf position, although that longwall advance was similar as in the phase A.
- Seismic activity rapidly increases in phase C when additional stress from advancing longwall face (75 m according to local rockburst guidelines) impacted area of remnant pillars in the fore field of longwall face. Seismic activity in this phase C is characterised mainly by a large number of recorded low energy seismic events (up to 10^2 J).
- 44 % of registered seismic events were recorded in the period of sub-phase C1 during the last 45 m of longwall advance.

4.2. Seismoacoustic monitoring
Evaluation of SA activity was carried out similarly to SL activity using the standard and also special tools for evaluation of seismic activity. Weekly and daily summary graph of SA events recorded from
the coal seam and SA events localisation map were selected for presentation. Registered SA activity during longwall advance is depicted in figure 4 and the map of registered seismic events in figure 7.

![Figure 7. Localisation of registered SA events (square goaf position of the longwall on the left, all registered SA events during longwall advance on the right).](image)

Recorded SA activity had classical development. SA events were recorded mainly from part of the coal seam impacted by previous mining (see figure 7). SA events were recorded approximately 100 m ahead of the advancing longwall face but in the area of pillars left from R&P trial, at the start of the longwall advance (see example in figure 7). The final longwall phase C (accordingly to SL monitoring evaluation) was selected for presentation. Increasing SA activity was recorded in this phase (see figure 7). SA activity was localized mainly in the remnant pillar of R&P trial and pillar between the main gate and the parallel gate. SA activity in the remnant pillar from R&P trial is interesting from two point of view. At first, fracturing of the pillar was recorded continuously from the very beginning of the longwall advance (360 m away). Then, fracturing of the pillar (i.e. recording of SA events) took place in the SW half of the pillar only as can be seen from locality of the SA events (see figure 7).

Main reason for the recorded SA activity in the presented phase of the longwall advance is:

- The remaining pillar from R&P trial was fractured within its South-West half, which was supported by recorded continuous floor heave in the main gate of the longwall (one side of the pillar).
- Continuous fracturing of the coal in the remnant pillars ahead of the advancing longwall face documented by SA events recording represent decreased accumulated energy in the coal seam and decreasing rockburst risk level in this area.
- Large amount of SL events recorded in the final phase of the longwall advance is probably connected with fracturing process in the coal seam recorded due to SA observation.

5. Conclusions

Seismic observations during longwall mining are important part of rockburst prevention. Presented results shows that extension of classical scheme of SL and SA observations using more stations yields satisfactory results. Extension of seismic network using more stations brings more accurate seismic events locations and to allow detail interpretation of rock mass fracturing during longwall advance. SL activity is sensitive to longwall advance mainly in the phase when longwall advance equal to the width and in the area of longwall panel termination. Seismic activity rapidly increases in phase when additional stress from advancing longwall face (75 m according to local rockburst guidelines) impacted area of
remnant pillars ahead of the longwall face. Seismic activity in this phase C is characterized mainly by a large number of recorded low energy seismic events. SA observations show that the remnant pillar of R&P trial was fractured in its SW half, which is also supported by recorded continuous floor heave in the main gate of the longwall (one side of the pillar). The SA events recorded the continuous fracturing of the coal in the remnant pillars ahead of the advancing longwall face showing decrease of accumulated energy in the coal seam and decreased rockburst risk level in this area.

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