Comparison of the results of the seismic profiling and WAS-96/RMS seismoacoustic active method in an assessment of the impact of the overlying coal seam edge

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Abstract. In the study, a comparison between the results of seismic profiling and the active seismoacoustic method WAS-96/RMS has been presented. The methods were used to assess the impact of an overlying coal seam edge on the relative stress state of the test heading in the chosen hard coal mine in the Upper Silesian Coal Basin, Poland. The work presents the methodologies of measurement, processing and interpretation of both methods. In the research area there were two edges of the adjacent seams at vertical distances of 70 and 100 m. The obtained results allowed for the development of conclusions regarding the effectiveness of both methods. It was stated, that the seismic profiling method, as well as the WAS-96/RMS method allowed for the identification of anomalies in the area of impact of the overlying coal seams. Based on previous experience, a comparison of the advantages and limitations of the seismic profiling and the WAS-96/RMS method has also been presented. As a result, it was found that seismic profiling should be the basic method for assessing the impact of the edges and remnants of exploited seams, whereas the WAS-96/RMS method may be used as a complementary method if a confirmation of the rockbursts threat is required.

Keywords: hard coal mining, seismic threat, stress concentration, edges of coal seam, seismic profiling, seismoacoustic method

1 Introduction

The seismic threat in Polish hard coal mines is associated with many factors of natural and mining origin [1–6]. One of the basic ones is stress concentration in coal seams which occurs in particular as a result of the impact of the edges and remnants of adjacent coal seams [7–

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9]. The magnitude of such impacts is commonly recognized by seismic profiling [1, 10–18]. Refracted P-wave velocity profiling used to be performed according to the Dubiński method [10] updated in the work of Dubiński and Konopko [1]. Szreder et al. [15] made significant progress in the field of seismic data processing and its interpretation.

The assessment of the seismic threat in coal mine excavations may also be carried out using the active seismoacoustic method WAS-96/RMS developed by Kornowski et al. [19]. This method allows for the assessment of the seismic threat on the 10 m long section of the coal seam.

The aim of the study is to compare the results of both methods - seismic profiling and WAS-96/RMS in identical conditions of impact of the overlying edges of coal seams. Both methods are based on different parameters. In seismic profiling, the refracted P-wave is determined, while in the WAS-96/RMS method the Z_{RMS} parameter is determined on the basis of energy intensity and the activity of the induced seismoacoustic emission.

The work presents the methodologies of measurement, processing and interpretation of both methods. The research was carried out in one of the hard coal mines in the Upper Silesian Coal Basin (USCB). In the area of research, there were two edges of adjacent seams at vertical distances of 70 and 100 m. The obtained results allowed for the development of conclusions regarding the effectiveness of both methods.

2 Methodology

2.1 Seismic profiling method

Measurement methodology

Depending on the conditions of propagation of the refracted P-wave in a coal seam [18]:

- The length of spread for 24 geophones may reach up to 115 meters adjusted to the energy of the wave source. The geophone interval should be assumed to be from 2 to 5 meters depending on the possibility of identifying refracted P-waves.
- The 40 Hz geophones are usually fixed on short anchors a few centimeters long in coal seam that is not intensively fractured or separated fragments.
- The seismic wave is excited with the use of a stroke with a sledgehammer of 5 kg.
- For improvement of the signal to noise ratio, at least six fold stacking should be applied.
- The seismic records are legible even in longer sections in the case of a low level of seismic noise and high amplification in the test equipment of the order of over 100 dB.
- The recording time and signal sampling always have to be tested in a specific investigation site. On the basis of previous experiments, one should select a sample interval of 0.125 ms and recording length of 0.5 sec.

Methods of processing and interpretation

In the interpretation stage, a two-layer model of a medium consisting of a fracture zone (plastic zone) and a solid zone (elastic zone) is assumed [15]. The reciprocal travel times method is used to calculate the velocity model and width of the fracture zone. The velocity model is corrected by the reverse analysis method. By changing the position of the seismic boundaries of the model, the calculated hodographs are adjusted to the observations. The accuracy of the calculations is verified by minimizing the average square error. In the final stage, velocity changes were compared with the reference velocity V_0 determined from the Dubiński empirical equation [10]:

$$V_0 = 1200 + 4.83H^{0.76} \tag{1}$$

where:
H – depth of survey area [m].

The reference velocity V_0 and the measured velocity V_P were used to calculate the percentage anomaly A according to the formula:

$$A = \frac{V_P - V_0}{V_0} \cdot 100\ [\%] \tag{2}$$

The calculated anomaly is applied to evaluate the relative stress state based on the seismic scale, determined for USCB conditions (Tab. 1) or measured velocity in the region outside of anomaly. The error of the measured velocity did not exceed 50m/s [18].

Table 1. Seismic scale of relative stress changes in Upper Silesian Coal Basin conditions (on the basis of [1]).

Degree of relative stress increase (decrease)	Positive (negative) seismic anomaly [%]	Scale of relative stress increase (decrease)	Probable increase (decrease) in relative stress [%]
0	< 5 (>-7.5)	Lack / very low	< 20 (<25)
1	5 – 15 (-7.5 ÷ -15)	Low	20 – 60 (25 ÷ 55)
2	15 – 25 (-15 ÷ -25)	Medium	60 – 140 (55 ÷ 80)
3	> 25 (< -25)	High	> 140 (>80)

2.2 Method of WAS-96/RMS

Measurement methodology
The measurement of seismoacoustic emission (SE) is carried out using two geophones (A and B) spaced symmetrically at a distance of 5 m from the blasthole in the coal seam (Fig. 1). Sensors should be placed as near as possible to the middle of the coal seam. The depth of the blasthole is 3 m, while the geophones holes are 1.5 m deep. A 1 kg charge of explosives is blasted.

The registration of SE is carried out in two-minute intervals and it lasts for 40 minutes. During the first 10 minutes, the SE noise is observed, and for the next 30 minutes the induced SE is observed as a result of blasting.

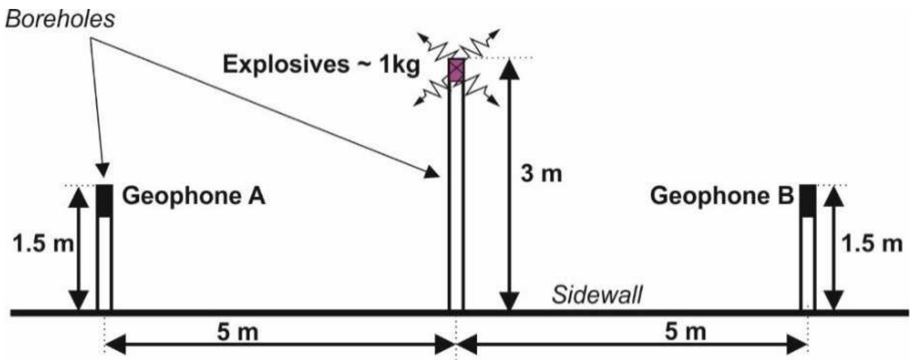

Fig. 1. The scheme of WAS-96/RMS measurement.

The measurement is carried out with the use of WLIS apparatus - multichannel seismoacoustic pulse counter or an equivalent apparatus from the point of view of the WAS-96/RMS method. WLIS enables the automatic counting of seismoacoustic pulses and the calculation of their energy. The apparatus records pulses with a sampling frequency of 5 kHz and dynamics of 60 dB for each channel.

Making measurements using the WAS-96/RMS method is possible only in conditions of seismic silence, without disturbances generated by mining works. Research in the freshly exposed sidewall may be undertaken 4 hours after the completion of mining.

Methods of processing and interpretation

The average pulse energy released in the two-minute intervals measured in Joules is given by the formula [19]:

$$\overline{\mathrm{E}} = 10\frac{(E^{A}_{WLIS} + E^{B}_{WLIS})}{40N} \tag{3}$$

where:

E^{A}_{WLIS} and E^{B}_{WLIS} – pulses energy from channels A and B in Joules,

N – total number of pulses on both channels.

Seismoacoustic activity and energy density in the time domain are estimated from formulas [19]:

$$n(t) = n_{-} + B\exp(-\beta t) + \eta_1 \tag{4}$$

$$E(t) = n(t)\overline{\mathrm{E}} + \eta_2 \tag{5}$$

where:

n_{-} – median of seismoacoustic activity before blasting,

$B = n_1 - n_{-}$ where n_1 is seismoacoustic activity in the first two minutes after blasting,

β – attenuation factor after blasting,

η_1, η_2 – constants of random disturbances.

The values of the parameters: n_{-}, B, β i $\overline{\mathrm{E}}$ fully characterize the measurement results. On the basis of measured parameters, the plots of activity and energy density changes for sensors A and B are made separately (Fig. 2). The graphs should be calibrated, so that the maxima of energy density and activity overlap with each other. The graphs are used to determine the time of increase in seismoacoustic activity after blasting (T_A and T_B).

The rockburst threat assessment is carried out on the basis of the Z_{RMS} parameter, which is calculated using the formula [19]:

$$Z_{RMS} = C_1 + C_2 n_{-} + C_3 B + C_4 \beta^{-1} + C_5 \overline{\mathrm{E}} \tag{6}$$

where:

C_1, C_2, C_3, C_4, C_5 – weighting constants specifying the correlation between the measured parameters and the rockburst threat. They are recalculated after every survey in the same site.

The calculation of the Z_{RMS} parameter is performed for each channel separately, and then a greater value of the Z_{RMS} parameter is selected for the analysis. The criteria for assessing the threat of rockbursts using the WAS-96/RMS method are given in Table 2.

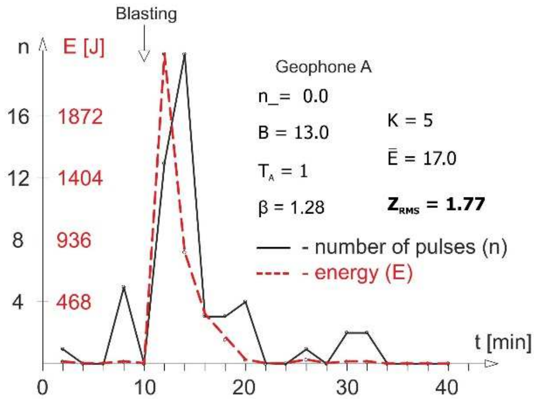

Fig. 2. Graph with parameters calculated in point P5 using WAS-96/RMS.

Table 2. Criteria for assessing the rockburst threat with the WAS-96/RMS method.

Z_{RMS}	Rockburst threat degree
$Z_{RMS} \leq 0{,}5$	No occurrence – a
$0.5 < Z_{RMS} \leq 1.5$	Weak – b
$1.5 < Z_{RMS} \leq 2.5$	Medium – c
$2.5 < Z_{RMS}$	High – d

3 Research area and geological - mining conditions

The measurements were conducted in the region of a planned A longwall in the X0 coal seam (Fig. 3). The seismic profiling and seismoacoustic measurements were conducted in the A1 heading at a depth of about 1200 m. The measurements were located in the impact zone of the overlying edges of the X1 and X2 coal seams, lying about 70 m and 100 m above the X0 coal seam.

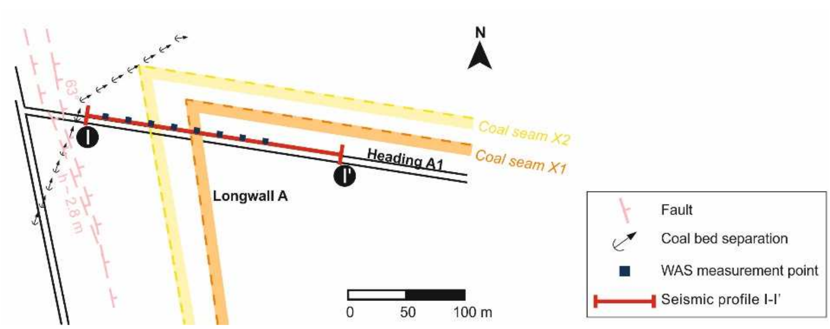

Fig. 3. Location of the seismic profile and WAS-96/RMS measurement points on the mining map with overlying coal seams edges and tectonic disturbances.

In the research area, the X0 coal seam has a mean thickness of about 3.6 m. The slope of the coal seam is between 0 and 5° in the N direction. The X0 coal seam is surrounded by mudstone layers of 3.9 m in thickness as the immediate roof. Above the mudstones there lies a sandstone layer of about 20 m in thickness. On the 20th meter of the heading A1 from the west side, there is a 10 meters wide fault zone with a maximum throw of 2.8 m and approximate angle of dip 63°/NEE. Separation of X0 coal seam occurs in the vicinity of the fault zone.

Seismic profiling was performed along the I-I 'profile (Fig 3). Geophones of 40 Hz were spaced out every 5 m over a distance of 200 m along the northern sidewall of the A1 heading. They were fixed approximately in the middle of the coal seam. The seismic wave was excited by a 4 kg sledgehammer at points located between the geophones. A sampling time of 0.125 ms and a registration time of 0.5 s were used. Six-fold vertical stacking was applied at each blasting point.

WAS-96/RMS measurements were made using the WLIS apparatus. Eight blasting boreholes spaced 20 m from each other were drilled. An explosive charge of 1 kg was blasted. Two 10 Hz geophones were symmetrically installed at each measuring point from both sides of the blasting borehole. The observation time of SE at a given point was 40 min.

4 Results and analysis

Figure 4 presents the results of seismic profiling and the active seismoacoustic WAS-96/RMS method together with the mining situation.

Seismic profiling

The velocity of the refracted P-wave on the profile varies from 2346 to 2457 m/s.. Two anomalous increases in the velocity of the P-wave are observed. The first anomaly A_1=4.9% is on the initial section of the profile up to approx. 25 m. It is probably associated with close proximity to the fault zone and the coal bed separation zone. The second anomaly A_2=8.4% occurs on the section from approximately 60 to 130 m of the measurement profile. The anomaly value was calculated for the reference velocity of V_0=2260 m/s. The A_2 anomaly is weak, which corresponds to an increase in stress in the range of 20 to 60%. Presumably, the anomaly A_2 is the effect of the impact of the edge of the X1 seam, and to a lesser extent the impact of the X2 edge.

The seismic profile is in large part underneath the gobs of the X1 and X2 seams. The effect of the stress reduction of these gobs is weak due to the impact of the edges of the X1 and X2 seams parallel to the profile (Fig. 3).

WAS-96 / RMS measurements

The value of the Z_{RMS} coefficient characterizing the rockburst threat level varies from 0.84 to 2.23 (Fig. 4b). The greatest value of the coefficient was obtained for the P1 measuring point, which may be related to the proximity of the fault zone and the X0 coal seam separation zone. At the next three measuring points, the values of the coefficient range from 0.84 to 1.21 indicating a weak rock burst hazard threat. At point P5, located directly under the edge of the X1 seam, the value of the Z_{RMS} coefficient increases and amounts to 1.79, this corresponds to the medium threat degree. In points P6 - P8, the values of the coefficient are smaller and do not exceed the value of 1.37.

Figure 4c shows graphs of the average energy of pulses and energy density in two-minute intervals. The character of both graphs is similar to the ZRMS coefficient graph. The maximum mean value of the energy pulse amounts to En=17 J and was measured at P5.

Diagram 4d shows two graphs of the average number of pulses over two-minute intervals. The first graph concerns the registration after blasting within 30 minutes. The second graph also includes pulses from 10 minutes registration before blasting. The greatest values of the average number of pulses were measured at points P1 and P2 and were respectively 6 and 10 pulses per 2 min. Increased seismoacoustic activity is probably related to the proximity of the fault zone and the X0 coal seam separation zone. The number of pulses measured at the remaining points is smaller and amounts to approximately 1 - 3 pulses per 2 min. There was no increase in activity at the edge of the X1 seam.

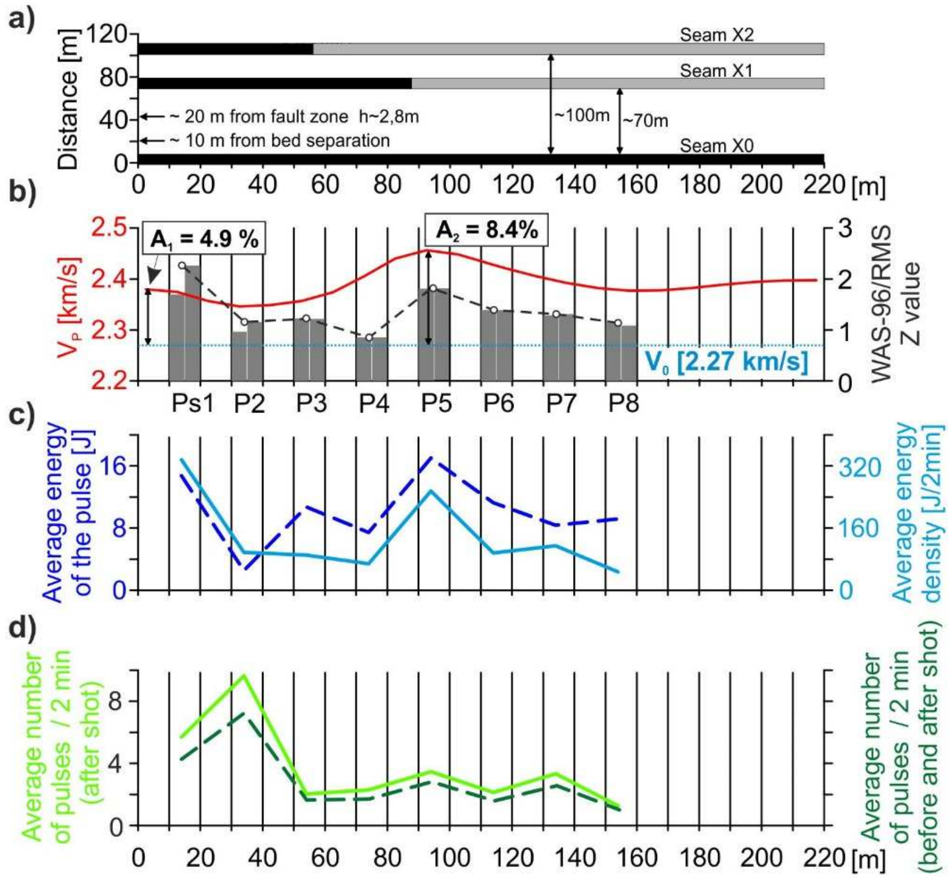

Fig. 4. Comparison of the results of seismic profiling and active seismoacoustic method WAS-96/RMS; a) coal seams edges location; b) refracted P-wave velocity in coal seam (solid red line – measured value, dashed blue line - reference value) and Z_{RMS} parameter from WAS-96/RMS measurements (grey bars - value for each geophone); c) average energy of the pulse and energy density; d) average number of pulses obtained from WAS-96/RMS measurements.

When comparing the results of the measurements of seismic profiling and the WAS-96/RMS method, a similarity may be observed in the presence of anomalous zones in the area of impact of the overlying coal seams. The anomalous increases in measured parameters: P-wave velocity, ZRMS parameters and average energy are clearly correlated. In contrast, the course of the seismoacoustic activity is different. The smaller number of pulses may explain why the stronger pulses appeared in the zone of greater impact of the overlying edges.

On the basis of up to date studies, a comparison of the advantages and limitations of the seismic profiling method and the WAS-96/RMS method is presented (Tab. 3 and 4).

Table 3. Advantages and limitations of seismic profiling.

Advantages	Limitations
• Changes in the P-wave velocity in the coal seam correspond to changes in relative stress. • Measurement is carried out in-site on the threatened section of excavation. • Survey is non-destructive. • The acquired information may be considered as continuous. • Measurement is relatively short in time (2 h for 100 m profile according to the described methodology). • Measurement cost is relatively low.	• High impact of mining disturbances on wave field registration. • Complicated wave image requiring experience in data processing and interpretation. • Great influence of the disturbed zone in the sidewall of excavation at the site of sensor installation on the recording quality. • Reduction of increments of the refracted P-wave velocity with increasing stress (problem at greater depths). • Necessity to maintain the seismic silence during the measurement in the research area (about 20 minutes per 100 m of profile). • Disturbances in the registration of seismic waves associated with complex tectonics and lithology (faults, seam thinning, washouts, rock partings, dirt bands). • The use of non-intrinsically safe measuring equipment is possible in an atmosphere of up to 0.5% of methane in accordance with applicable regulations.

Table 4. Advantages and limitations of WAS-96/RMS method.

Advantages	Limitations
• Changes in the density of energy of seismoacoustic emission correspond to stress changes in the coal seam. • Measurement is carried out in-site on the threatened section of excavation. • Processing and interpretation of seismoacoustic data is automated. • Adaptive algorithm is used to improve the calculation of the Z_{RMS} parameter.	• Zonal valid results of up to 10m wide. • Destructive test requiring blasting of 1 kg of explosives. • Relatively long time of measurement associated with the preparation of boreholes, loading explosives and blasting. • Necessity to stop mining work in the research area. • The measurement costs are relatively high. • Performing the measurement is limited by the possibility of the use of explosives in conditions of natural and mining hazards in accordance with applicable regulations.

5 Conclusions

In the study, a comparison of the results of seismic profiling and the WAS-96/RMS method carried out in identical measurement conditions of the impact of the overlying coal seam edges has been presented. Based on the analysis, the following conclusions were made:

1. Both the seismic profiling and the WAS-96/RMS method allowed for the identification of anomalies in the area of impact of the overlying coal seam edge (seismic anomaly A_2=8.4% - low degree and Z_{RMS}=1.79 - medium degree).
2. At the beginning of the measurement profile, both methods indicate an increase in the threat related to the vicinity of the fault zone and the coal seam separation zone. The anomalous increase of velocity A_1 is enough clear, but this is only a part of this anomaly. In the case of the WAS-96/RMS method, the degree of threat is more evident. This increase is marked clearly on the energy density graph (Fig. 4c). In this case, it is difficult

to indicate which of the methods has shown the seismic threat more correctly. The problem will be explained during the operation of the planned longwall A.

3. The seismic profiling method seems to provide more clear results. Measured velocity values provide approximately a continuous graph of their changes, which corresponds to relative changes in stress. In the case of the WAS-96/RMS method, we gain a discrete graph associated with the zonal measurement from the 10 m long section. The method proposed by the Kornowski et al. [19] also allows a 60 m long section, 30 m each side of the blasting hole, in the case of homogeneous conditions in the coal seam .
4. Costs and time of the measurements are more favorable for seismic profiling. The measurements of 200 m of seismic profiling takes about four hours with the engagement of approximately 4-5 people of the measurement group together with the mining superviser. In the case of the WAS-96/RMS method, seven measurements of approx. 30 m each over a distance of approx. 200 m requires at least two work shifts, with a group of at least seven people engaged: drill and blast miners, measurement operators and the mining superviser.
5. The results of the research indicate that seismic profiling should be the basic method for assessing the impact of the edges and remnants of exploited coal seams. The WAS-96/RMS method may be used as a complementary method if a confirmation of the rockbursts threat is required.

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