

Edges of overlying seams as a factor responsible for strong mining tremors occurrence during underground hard coal extraction in the light of seismic moment tensor inversion method

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Abstract. Physical processes occurring in the focus of tremor can be identified by solving a focal mechanism via the seismic moment tensor inversion method. In this article the estimation of focal mechanisms of strong mining tremors (according to Polish law tremors of energy higher or equal $1 \cdot 10^5$ J), which occurred during longwall mining of coal seam no. 507 in one of the hard coal mines in the Polish part of Upper Silesian Coal Basin was performed. Totally 7 strong mining tremors with the local magnitude from 1.84 to 2.52 were analysed. The most probable geomechanical processes in the foci of these tremors have been reconstructed. An attempt to determine the correlation between the edges of overlying seams no. 502, 504 or 506 and strong mining tremors occurrence has been made. The strike of determined nodal planes is in accordance with the azimuth of mentioned edges. The difference between them (absolute value) varies from 0.3° to 34.1° (on average approximately 19°).

Keywords: coal seam edge, mining tremor, focal mechanism

1 Introduction

Rockburst hazard accompanies the underground extraction of coal seams in the Upper Silesian Coal Basin (USCB). A rockburst is a dynamic and catastrophic phenomenon, relating with violent failure of coal seam or rocks, and causing the destruction of mine openings and supports. After it, underground excavations lose their functionality and destruction of machines or other underground infrastructure objects often takes place. Moreover, the rockburst is a real danger for miners, working in underground excavations.

There are many causes of rockburst occurrence in underground hard coal mines, e.g. growing depth of mining and increase of stress level, physical properties of coal seams (i.e. ability of coal seam to accumulate strain energy) and its thickness (dynamic floor heaving hazard), fracture of competent waste rocks being a source of high-energy tremors, and geological discontinuities (faults) and folds, vicinity of protecting pillars, and presence of coal seam edges (or remnants left unmined), increasing the level of stress in the rock mass.

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The sources of rockburst hazard have to be correctly defined, and rockburst prevention should be focused on them.

Rockburst and seismic hazards are correlated with each other. By analysing the seismic activity and processes occurring in the focus of mining tremors, factors affecting the rockburst hazard can be recognized.

The focal mechanism can be determined with the use of the seismic moment tensor inversion method. This method enables estimation, what kind of processes were present in the focus of tremor (e.g. explosion or implosion, uniaxial compression or tension, shear). This can be further correlated with geological or mining factors.

In this article, we have analysed the focal mechanism of 7 strong mining tremors (energy $\geq 1 \cdot 10^5$ J), which occurred during longwall mining of coal seam numbered 507 in one of the hard coal mines, located in the Polish part of Upper Silesia Coal Basin (USCB), on the main anticline. We try to investigate if their occurrence was correlated with the edges of coal seams numbered 502, 504 and 506, laying over the coal seam no. 507. In the light of obtained results, an evaluation of rockburst prevention for selected longwall has been made.

2 Rockburst hazard in the Polish part of USCB

In the last 15 years, more than 18.5 thousands of strong (high-energy) tremors ($\geq 1 \cdot 10^5$ J) have been recorded in mining plants, and 36 of them caused rockbursts. The stabilization of annual number of strong tremors in the last 6 years, despite the decrease of total coal extraction is shown on Fig. 1. The reasons of rockbursts may be different [1], as it was mentioned above.

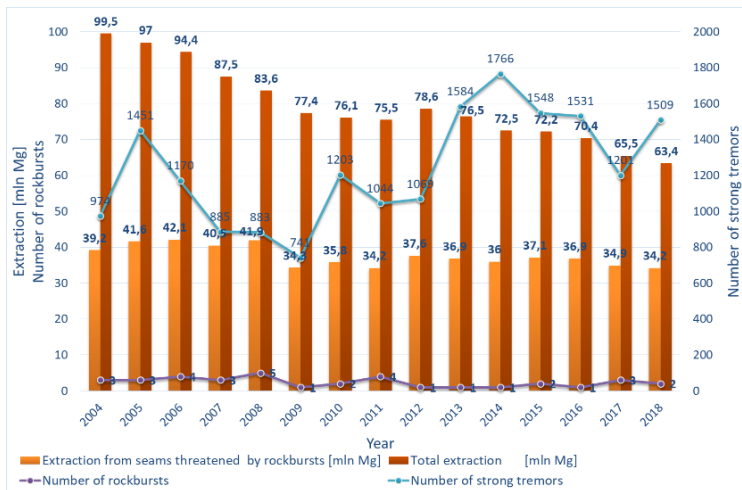


Fig. 1. An annual number of strong tremors and rockbursts in the Polish part of USCB against the annual extraction of hard coal (total and from seams threatened by rockburst) [2].

In the last 15 years, the annual total energy of strong tremors equalled averagely 3.2 GJ. Whereas in 2015 and 2018 the sum of energy of strong tremors had anomalous values and equalled 9.71 and 8.74 GJ respectively. In the remaining period of time the average sum of tremors energy was 2.29 GJ [2]. Such anomalous values were mainly caused by the occurrence of some very strong tremors with the tectonic origin or triggered during extraction under complicated conditions, where a set of edges and remnants of other coal seams was present. Furthermore, although the total coal extraction decreases, the extraction of coal seams threatened by rockburst remains at a comparable level.

3 Site characterization

3.1 Geological and mining conditions affecting the rockburst hazard

A thick coal seam no. 507 (3-4.1 m) was extracted in the selected hard coal mine at large depth, i.e. from 814 m to 884 m below surface (from -564 m to -634 m b.s.l.). The inclination of this coal seam equalled 2°-16°, and was generally from WNW to ESE. The longwall system with caving was applied, and longwall face run was downhill. The length of longwall face equalled about 198 m, and its height was 3.8 m. Both, depth of exploitation and thickness of coal seam no. 507 were negative factors. Another was an ability of coal seam no. 507 to accumulate strain energy and its sudden release. The uniaxial compressive strength of this coal seam was above 16 MPa.

A presence of competent sandstones in the roof of coal seam no. 507 was negative for rockburst hazard, because fracturing of these rocks may be correlated with the high-energy tremors occurrence. In the immediate roof, thin layers of shale and locally sandy shale were present, and above them a few-metre layer of sandstone, with uniaxial compressive strength of about 70 MPa was deposited. In a distance of about 30 m from the coal seam no. 507, thick layers of sandstones (with uniaxial compressive strength of about 80 MPa) were present, occasionally interbedded, mainly by layers of sandy shales.

In the floor of coal seam no. 507 layers of shales and sandy shales were deposited (with total thickness from 2.1 m to 8.6 m). Below them, a thick coal seam 510 was deposited (maximum thickness about 8.5 m). Presence of soft rocks in the floor of coal seam no. 507 threatened with its dynamic upheaval.

Over the longwall panel, extraction of coal seams numbered 502, 504 and 506 was made in the past. Coal seam no. 502, deposited at about 124 m above, was extracted from 12 to 22 years earlier. Coal seam no. 504, deposited at about 61-70 m above, was extracted from 10 to 13 years earlier. Extraction of coal seam no. 506, deposited at about 27 m above, was the earliest, i.e. 36-37 years before the extraction of coal seam no. 507.

The longwall panel was in total under the goaf made in coal seam no. 502. It was a positive factor concerning rockburst hazard. Extraction of other coal seams numbered 504 and 506 created edges over the longwall panel. In the vicinity of seam edges the stress level in rock mass potentially increases [1]. The edge of the coal seam no. 504 was placed on the east side of longwall panel, in the area of the tail gate. Over the longwall panel, it had a triangular shape. Coal seam no. 504 had been extracted there by two separate longwalls (one from the south to the north – 13 years earlier, and one from the east to the west – 10 years earlier). Edge of seam no. 504 was also present on the southern side of longwall panel, where the end of coal seam no. 507 mining with selected longwall was planned, in the area of the main gate. In the past, the extraction of coal seam no. 507 was made after the destressing extraction of coal seam no. 506. Unfortunately, coal seam no. 506 became thinner to the south, and its favourable extraction could not be continued. Edge of coal seam no. 506 was on the northern side of longwall panel, and a part of longwall cross-cut was theoretically under the negative influence of it. Longwall face started advancing in the area below goaf made in coal seams numbered 502, 504 and 506. Extraction of coal seam no. 507 below goaf of overlying seams was positive because of destressing of the rock mass. However, the stress increase near the edges of overlying coal seams was expected.

3.2 Seismicity during longwall mining

During longwall mining of coal seam no. 507 with selected longwall, totally 1810 tremors occurred, releasing in total $1.4 \cdot 10^7$ J of energy. Concerning low-energy tremors, 1352 of them had the energy of 10^2 J ($0.11 \leq M_L < 0.63$) and 330 of them had the energy of 10^3 J

($0.63 \leq M_L < 1.16$). Totally 121 medium-energy tremors occurred, but 23 of them were provoked by the long-hole destress blasting in roof rocks or blasting for caving. They had the energy of 10^4 J ($1.16 \leq M_L < 1.68$). Concerning strong tremors, 5 of them had the energy of order of 10^5 J: $4 \cdot 10^5$ J ($M_L = 2.00$), $2 \cdot 10^5$ J ($M_L = 1.84$), $6 \cdot 10^5$ J ($M_L = 2.09$), $3 \cdot 10^5$ J ($M_L = 1.94$), $9 \cdot 10^5$ J ($M_L = 2.19$), and 2 of them had the energy of order of 10^6 J: $4 \cdot 10^6$ J ($M_L = 2.52$) and $1 \cdot 10^6$ J ($M_L = 2.21$). Presented values of the local magnitude M_L in brackets were calculated according to the formula $\log E = 1.8 + 1.9M_L$ given by [3].

Seismic activity clearly corresponded with the range of earlier extraction of coal seam no. 504 (deposited at about 61-70 m above coal seam no. 507). Most of the low- and medium-energy tremors occurred in the first stage, where the extraction of coal seam no. 504 had been made about 13 years earlier. The seismic activity was lower in the second stage, where coal seam no. 504 had been extracted about 10 years earlier (Fig. 2), and the larger effect of destressing of the rock mass was observed. However, near the edge of seam no. 504, extracted about 10 years earlier, a higher stress level was expected.

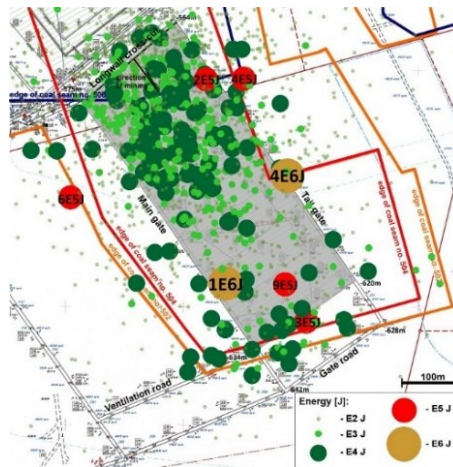


Fig. 2. Seismic activity during the extraction of coal seam no. 507 with selected longwall.

The focal mechanism of 7 above mentioned strong mining tremors has been determined via the seismic moment tensor inversion method.

4 Seismic moment tensor inversion method

A point seismic source can be represented by the seismic moment tensor (SMT). It can be determined by the waves which wavelengths are much longer than the linear dimensions of the source [4]. The seismic moment tensor describes the force system acting in the seismic source [5], represented by sets of two vectors (Fig. 3).

For three components of force and three possible arm directions, there are nine generalized couples [4]. The seismic moment tensor can be written in a form of square matrix 3×3 as:

$$M = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix} \quad (1)$$

It is a symmetric tensor describing nine couples of equivalent dipole forces which can act at the seismic source [6]. Each component of the presented matrix characterizes one of the nine

possible force couples. Diagonal components ($i = j$) represent linear vector dipoles, and the other components ($i \neq j$) represent force couples with seismic moment tensor.

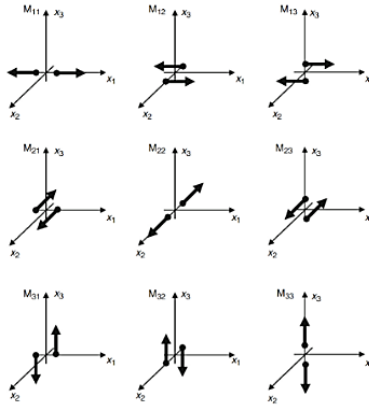


Fig. 3. Nine generalized couples of forces M_{ij} ($i = 1, 2, 3, j = 1, 2, 3$) forming the moment tensor [6].

The seismic displacement field, radiated from the seismic source, is defined, as a convolution in the time domain of the moment tensor and the spatial derivatives of the Green's function [7]. It is assumed that all of the seismic moment tensor components depend similarly on time. Assuming the source function to be equal to the Dirac's delta function, the displacement vector is described as:

$$u_k(x, t) = M_{ij} * \frac{\partial G_{ki}}{\partial x_j} = M_{ij} * G_{ki,j} \quad (2)$$

where M_{ij} is a moment of the force couple acting in the direction of the x_i axis and with arm directed along the x_j axis, G_{ki} is a Green's function representing the impulse response of the medium on the distance travelled by the seismic wave, $G_{ki,j}$ is a spatial derivative of the Green's function after x_j , and sign * means an operation of the convolution [4-6].

The displacement in the far-field, caused by the system of forces acting in the tremor focus, is the sum of the displacements caused by the particular force couples [4]. The recorded displacements enables the SMT inversion.

To identify the geomechanical processes occurring in the focus of tremor, the decomposition of seismic moment tensor is applied. This tensor can be decomposed into an isotropic component (I) and deviatoric component, including compensated linear vector dipole (CLVD) and double-couple of forces (DC):

$$M = |M_I| + |M_{CLVD}| + M_{DC} \quad (3)$$

The isotropic component (I) describes volumetric changes (the positive sign means explosion, the negative sign means implosion). The CLVD component is related to uniaxial tension (positive sign) or compression (negative sign). The DC component describes shear and slide along the failure plane. Full seismic moment tensor inversion enables the determination of percentage share of I, CLVD and DC components. For the DC component, the nodal plane parameters (strike angle Φ , dip angle δ , rake angle λ) are calculated. These planes (named usually as A and B) separate areas of compression and dilatation, and one of them is a real failure plane, while the second one is an auxiliary plane, perpendicular to the slip movement [8].

The SMT inversion method was firstly applied in global seismology to study natural seismic sources [9, 10], where shear and slip on fault planes dominate. But the moment tensor

description covered also other types of seismic sources (e.g. being a result of explosion or implosion, fluid injection, volcanic eruption etc.). The seismic moment tensor inversion method due to its flexibility, was successfully adapted to study mining-induced seismic events with complicated mechanism [11-21].

This method has been applied to determine the focal mechanism of strong tremors induced by longwall mining of coal seam numbered 507 in one of the hard coal mines in the Polish part of USCB. Because of the fact, that in the focus of mining induced tremors often non-double-couple components (I and CLVD) are present, the full seismic moment tensor inversion was done.

5 Results

Focal mechanisms of strong tremors have been estimated with the use of the seismic waves generated in their foci and registered by the mine seismic network, consisted of 15 underground seismic stations (short-period SPI-70 seismometers and low-frequency DLM-2001 geophones, measuring the vertical component of ground motion velocity). These seismic stations were located at a depth from -160 m to -1000 m below sea level (-410 m to -1250 m below surface). The error of epicenter location ranged from about 25 m to about 38 m, and for the vertical coordinate Z it was between about 47 m and about 59 m (assuming seismic wave first arrival time error of 10 ms and velocity model error of 20 m/s). The P-wave onsets were picked manually and amplitude inversion in the time domain was done in the FOCI software [8]. The Z coordinate of each focus of strong tremor was improved by the FOCI software [8], testing the full solution for the lowest value of estimation error and the highest value of quality coefficient (depending on the configuration of seismic stations). Both norms: L1 and L2 were taken into calculations, and gave convergent results. Because the norm L1 has lower dependence on possible large errors, caused e.g. by random noise produced by mining operation or transport machines, results obtained with it have been accepted as final (Table 1).

Table 1. Focal mechanism parameters of strong tremors during the extraction of coal seam no. 507.

No.	E [J]	Z^1 [m]	Components of full seismic moment tensor [%]			Type mechanism	Nodal plane parameters ²	
			I	CLVD	DC		$\Phi A / \delta A$ λA	$\Phi B / \delta B$ λB
1.	4E5	-455	25.2	28	46.8	RE/EXPL	234.8° / 68° 90.1°	54.6° / 22° 89.8°
2.	2E5	-508	26.3	27.4	46.3	RE/EXPL	235.9° / 59.8° 100.3°	36.1° / 31.7° 72.9°
3.	6E5	-404	22.3	10.7	67	RE	261.7° / 70° 64.9°	135.6° / 31.7° 139.4°
4.	4E6	-470	-25.2	-24.7	50.1	NO	237.1° / 78.2° -91.4°	63.9° / 11.8° -83.4°
5.	3E5	-576	8.7	14.5	76.8	RE	254.7° / 74.8° 99.9°	40.9° / 18.1° 57.5°
6.	9E5	-576	-37.1	-2.6	60.3	NO	351.7° / 62.3° -41.6°	104.1° / 54° -144.9°
7.	1E6	-558	-34.1	0.2	65.7	NO	338.3° / 58.6° -62.7°	113.4° / 40.7° -127°

¹ focus depth improved by the FOCI software (solution characterized by the lowest error value and the highest quality coefficient value),

² parameters of nodal planes: ΦA , ΦB – strike angle of nodal plane A, B; δA , δB – dip angle of nodal plane A, B; λA , λB – rake angle connected with nodal plane A, B.

The percentage share of the I, CLVD and DC components were calculated. If the DC component equals 50% or more, the solution has been classified by the authors as normal

(NO) or reverse (RE) slip mechanism, depending of the direction of rock blocks movement. If the share of DC component was lower than 50%, the mixed mechanism e.g. RE/EXPL (a combination of reverse slip mechanism and explosion) has been assumed. For all strong tremors the parameters (strike angle Φ , dip angle δ , rake angle λ) of two perpendicular nodal planes (A and B) have been calculated (Table 1).

The foci depth calculated from the best-fitting solution by the FOCI software ranges from -404 m to -576 m below sea level (Table 1). It clearly corresponds with the depth of the roof rocks of coal seam no. 507 (from 50 m to 190 m above coal seam no. 507).

In all cases, a shear mechanism dominated. The share of the DC component for these tremors varies from 46.3% to 76.8% (average 59%). In 4 cases a reverse slip mechanism dominated, but in 2 of them the share of the DC component was below 50%, so they have been classified as RE/EXPL. In the focus of three of the strongest tremors a normal slip mechanism occurred. The share of the I component (absolute value) ranges from 8.7% to 37.1% (average 25.6%). The CLVD component has the lowest share in the full solution of the seismic moment tensor or is comparable with the share of the I component – absolute value between 0.2% and 28% (average 15.5%).

A map of coal seam no. 507 with the beachballs, representing focal mechanisms of strong mining tremors is shown in Fig. 4. In each beachball, the shaded area indicates tension, the white area indicates compression, and continuous lines show the projection of nodal planes on the lower hemisphere. The size of beachballs is correlated with the order of energy of mining tremor.

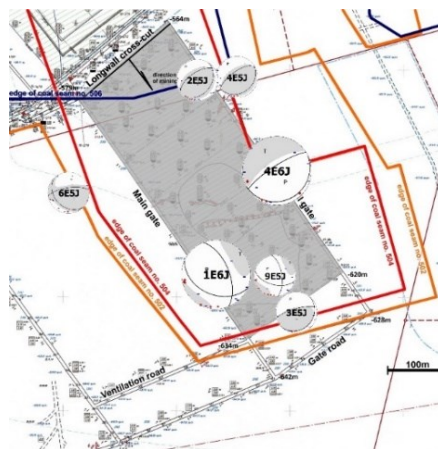


Fig. 4. Map of coal seam no. 507 with beachballs representing the focal mechanism of strong mining tremors.

Focal mechanism of the first two strong tremors ($4 \cdot 10^5$ J, $2 \cdot 10^5$ J) was similar. It concerns both the percentage share of full seismic moment tensor components, and nodal planes parameters. A mixed mechanism, consisting of reverse slip mechanism and explosion (RE/EXPL) was present there. The reverse slip mechanism occurs if the high horizontal stresses are present in the rock mass. The strike angle of nodal plane A for these tremors ($\Phi_A = 234.8^\circ$ and $\Phi_A = 235.9^\circ$) correlates with the azimuth of the edge of coal seam no. 502, located on the eastern side, out of the longwall panel, and the azimuth of the edge of coal seam no. 506 (in both cases about 258°) – Fig. 5a. For easier comparison, the azimuth of the edge of overlying coal seam in the vicinity of focus has been measured clockwise from the north direction, in an analogous way as the strike angle of nodal plane presented in the text. To draw the azimuth of coal seam edge in Fig. 5 two values of angles have been determined: the first angle is measured clockwise from the north direction and the second angle equals the first one plus 180° . If the position of coal seam edge changes near the epicentre of the

selected tremor, all corresponding azimuths are presented in Fig. 5. The rock blocks movement in the focus of the first two strong tremors (Fig. 5a) was in the direction of mining ($\lambda A = 90.1^\circ$ and $\lambda A = 89.8^\circ$). The focus of the first tremor was about 120 m over the coal seam no. 507, what corresponds with the edge of coal seam numbered 502 (about 124 m above) or competent roof rocks of coal seam no. 504 (sandstones). The focus of the second tremor was localized about 70 m over the coal seam no. 507, what corresponds with the depth of coal seam no. 504 (about 61-70 m above) or roof rocks of coal seam no. 506 (deposited about 27 m above the coal seam no. 507). The position of longwall face, quasi-parallel to mentioned edges of coal seams numbered 502 and 506, could play an important role.

A similar mechanism as above was present in the focus of the third strong tremor ($6 \cdot 10^5$ J), but this time the reverse slip mechanism (RE) clearly dominated. The strike angle of nodal plane B ($\Phi B = 135.6^\circ$) correlates with the azimuth of the edge of coal seam no. 502 (about 153°) and no. 504 (about 160°) – Fig. 5b. The rock blocks movement was more horizontal ($\delta B = 31.7^\circ$), and in the direction of longwall cross-cut ($\lambda B = 139.4^\circ$). The focus of this tremor was about 190 m over the coal seam no. 507. The occurrence of this tremor was connected with the slip mechanism in deflected roof rocks of coal seam no. 502.

In the focus of the strongest tremor ($4 \cdot 10^6$ J) a normal slip mechanism (NO) dominated. Strike angle of nodal plane A ($\Phi A = 237.1^\circ$) and B ($\Phi B = 63.9^\circ$) could be in both cases correlated with the azimuth of the edge of coal seam no. 504, calculated in an analogous way, i.e.: 254° or 74° – Fig. 5c. In case of nodal plane A the rock blocks movement was almost vertical ($\delta A = 78.2^\circ$) and in the direction of goaf behind the longwall face ($\lambda A = -91.4^\circ$). Concerning the nodal plane B parameters, the movement was almost flat ($\delta B = 11.8^\circ$) and in the direction of mining ($\lambda A = -83.4^\circ$). In relation to geological and mining conditions, the rock blocks movement described by the nodal plane A is more probable. The focus of this tremor was localized about 120 m over the coal seam no. 507. It correlates with the depth of coal seam no. 502 or layer of competent roof rocks of coal seam no. 504 (sandstones).

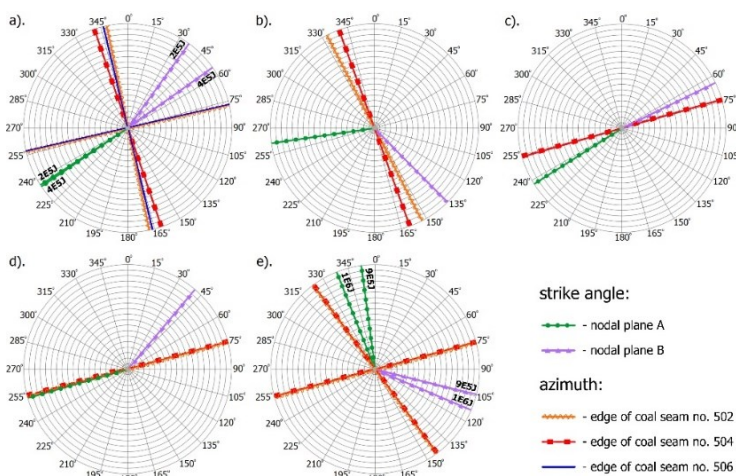


Fig. 5. Strike of nodal planes in the foci of strong tremors induced during longwall mining of coal seam no. 507 in comparison with the azimuth of edges of overlaying coal seams.

The reverse slip mechanism (RE) clearly dominated in the focus of the fifth strong tremor ($3 \cdot 10^5$ J). The strike angle of nodal plane A ($\Phi A = 254.7^\circ$) is almost identical with the azimuth of edges of coal seam no. 502 and no. 504 (in both cases about 255°) – Fig. 5d. The rock blocks movement was compatible with the direction of mining ($\lambda A = 99.9^\circ$). The focus of this tremor was localized about 50 m over the coal seam no. 507. The occurrence of this tremor was caused by the high level of horizontal stresses, near the edge of coal seam no. 504.

Focal mechanism of the last two strong mining tremors ($9 \cdot 10^5$ J, $1 \cdot 10^6$ J) was similar to each other. The normal slip mechanism dominated (NO), the share of implosion was high (-37.1% and -34.1%), and the CLVD component almost did not occur. The strike angle of nodal plane A ($\Phi_A = 351.7^\circ$ and $\Phi_A = 338.3^\circ$) correlates with the azimuth of edges of coal seam no. 504 and no. 502, situated on the western side of longwall panel (in both cases about 323°) – Fig. 5e. The rock blocks movement in the foci of the last two strong tremors was outward from the longwall panel. Foci of these tremors were appropriately about 50 m and 70 m over the coal seam no. 507, what corresponds with the depth of coal seam no. 504.

6 Discussion and conclusions

The most probable focal mechanisms of strong mining tremors, occurred during longwall mining of coal seam no. 507 in one of the hard coal mines in the USCB have been determined via the SMT inversion, and in all cases a shear mechanism was present. It has been confirmed, that the strike of nodal planes is in accordance with the azimuth of edges of overlying coal seams numbered 502, 504 and 506. The difference between them (absolute value) is in a range from 0.3° to 34.1° (on average approximately 19°). The improved depth of foci of strong tremors correlates with the depth of overlying coal seams (mostly with the coal seams no. 504 or 502) or their roof rocks.

The rockburst prevention for selected longwall was based on a long-hole destress blasting in roof rocks of the coal seam no. 507. Blastholes with the length of 45 m or 70 m were directed to the edges of overlying coal seams, mostly outward of the longwall panel. The main aim of this blasting was to destress the rock mass in the surroundings of the longwall panel and to create the fracture zone in the roof of coal seam no. 507. The energy of immediately provoked tremors varied from $8 \cdot 10^3$ J ($M_L = 1.11$) to $5 \cdot 10^4$ J ($M_L = 1.53$). The energy of induced strong tremors was partly dissipated in the fracture zone, and the longwall face and galleries were protected.

In the light of presented results, the rockburst prevention for selected longwall in coal seam no. 507 was designed correctly. Edges of overlying coal seams, influencing the stress level in the rock mass, out of the longwall panel were the main factor responsible for strong mining tremors occurrence. They affected the rockburst hazard level in the highest degree.

Performed analysis has shown that seismic moment tensor inversion method could be a useful tool for rockburst prevention in underground hard coal mines.

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