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Keywords

coal mining, rock burst prevention, induced seismicity, seismic moment tensor

RESEARCH ARTICLE

Identification of strong tremor causes for appropriate rock burst prevention in a hard coal mine

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Abstract

The exploitation carried out in the Bielszowice part of the Ruda Hard Coal Mine is mainly accompanied by seismic and rock burst hazards. The occurrence of high-energy tremors may be associated with many factors, e.g., fracturing of thick layers of high-strength rocks or destruction processes of a stressed and/or thick coal seam. These factors are often combined when excavating a single longwall panel. Determining the causes of strong tremors is of fundamental importance for mining and rock burst prevention. The extraction of the 004z longwall panel in the top layer of coal seam No. 504 was designed in complex geological and mining conditions. During the mining of the 004z longwall panel, strong tremors with energies of 10^5 J and 10^6 J occurred. The analysis of the focal mechanisms of these tremors using the seismic moment tensor inversion method allowed to determine the most probable causes of their occurrence. They were mainly related to the processes of fracture and slip in the thick layers of sandstone deposited in the direct or main roof of coal seam No. 504. Therefore, active rock burst prevention was aimed mainly at fracturing high-strength roof rocks.

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1. Introduction

For several dozen years, in underground hard coal mines located in the Upper Silesian Coal Basin (USCB), the occurrence of rock bursts is observed and investigated [1−9]. Rock burst hazard is one of the basic natural hazards occurring in mines located in USCB, often affecting the shape and scope of exploitation, and in extreme cases, forcing the withdrawal from further exploitation. A rock burst is a sudden release of elastic energy accumulated in the rock mass, manifesting itself in rock mass vibrations, carrying significant energy, combined with acoustic phenomena and a shock wave [5]. This phenomenon causes the destruction of the rock structure of the roof rocks, floor rocks or seam with a simultaneous dynamic displacement of rocks into the excavation and causes the destruction of the support or machines and devices [5]. As a result of the rock burst, the functionality of the mining excavation is lost. Rock bursts can be classified according to the reasons for their occurrence. In-seam rock bursts (stress rock bursts) are correlated with dynamic destruction of sidewall parts of the seam as a result of the accumulation of strain energy in stress concentration zones in coal seams [10]. In turn, the cause of roof rock bursts (stroke rock bursts) is the dynamic fracture of a rigid complex of compact roof rocks disturbed by mining [10]. In hard coal mines, there are also mixed rock bursts, i.e. stroke-stress rock bursts, caused by the imposition of the dynamic load impulse caused by the fracturing of rigid rock layers on the already stressed sidewall parts of the seam [10]. In order to reduce the occurrence of rock bursts in the USCB, a number of theoretical, monitoring and preventive methods have been developed or adapted. Despite the systematic decline in production, the number of strong tremors and rock bursts in the USCB area has remained at a similar level for many years [11]. The reason for this is the exploitation of deeper and deeper coal seams in more and more complex

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geological and mining conditions – mainly due to the remnants and edges of previously mined seams and established protective pillars. Underground mining of hard coal seams in the Upper Silesian Coal Basin is currently carried out at great depths, usually between 500 m and 1000 m, but also more and more often below 1000 m. At such depths, the stress level in the rock mass reaches considerable values. The presence of geological disturbances (faults, folds, split of seams, etc.), as well as additional stress related to the remnants and edges of adjacent seams, is also important for the planned exploitation. Long-lasting and multi-seam mining is also associated with establishing protective pillars, where an increased level of stress is observed. Exploitation in the vicinity of such remainders may be associated with the release of accumulated strain energy. Thick layers of strong rocks, mainly sandstones, are present in the geological structure of the USCB. The fracturing of these rock layers is usually responsible for the strong tremors. During the designing of mining works, the strength parameters of coal and surrounding rocks are also taken into account, including their ability to accumulate strain energy. Moreover, the exploitation of the top layer of a thick seam may be accompanied by a floor heave. The occurrence of rock bursts in hard coal mines is therefore complex and depends on many factors. Designing the exploitation in conditions of a rock burst hazard involves, inter alia, the determination of the maximum forecasted seismic energy of tremors, the selection of the appropriate support for openings and the determination of the type and scope of rock burst prevention. In addition, during the mining, rock burst prevention is adjusted to the current state of rock burst hazard, e.g. additional long-hole destress blasting in roof rocks or destress blasting in coal seam are performed, additional geophones are installed, additional induced seismicity analyses are carried out, additional in situ seismic surveys are performed etc.

The study area is the Bielszowice part of the Ruda Hard Coal Mine. This mine is located in the USCB and recently exploits coal seams belonging to the 400 and 500 series, which are classified as 1st or 2nd (the highest) degree of rock burst hazard. The natural hazards here are dominated by the aforementioned rock bursts, as well as methane and spontaneous combustion hazards. These hazards are combined with each other; hence the proper design of rock burst prevention is of great importance [12–15]. In the Bielszowice part of the Ruda Hard Coal Mine, an extraction of 004z longwall panel in the top (under-roof) layer of the thick coal seam No. 504 and in complex geological and mining conditions was planned. The longwall panel was located between the protective pillars, i.e. the pillar for the flank drifts to the west and the pillars for the main drifts and shafts to the east. It was the first longwall in coal seam No. 504 in this part of the deposit. Based on the analysis of geological and mining conditions, already at the design stage of this mining, a number of activities were assumed as part of active and passive rock burst prevention, which were then supplemented based on the observed level of rock burst hazard and the analyses performed. During the mining of the 004z longwall panel, systematic studies of the accompanying seismic activity were carried out, including the use of the seismic moment tensor (SMT) inversion method, and underground seismic surveys were performed, mainly using the seismic tomography method. The article presents an analysis of the mechanisms of strong tremors that occurred during the mining of 004z longwall panel in coal seam No. 504 in complex geological and mining conditions, as well as the scope of activities performed as part of rock burst prevention. The selection of the factors most significantly influencing the rock burst hazard and the determination of rock burst prevention adequately to the level of the rock burst hazard was of significant importance for safe and effective exploitation.

2. Geological and mining conditions

The mining of the 004z longwall panel in the top layer of coal seam No. 504 was performed in a longitudinal system with caving, and the longwall face advance was from west to east. The thickness of the mined coal seam layer was up to 3 m. The width of the 004z longwall panel was about 195 m, and its length equalled, on average, about 546 m. The 004z longwall panel was at a depth of about −572 m to about −615 m above sea level. The average depth of coal seam No. 504 in the area of longwall 004z was about 844 m below the ground level. This depth corresponds to a theoretical stress level of about 21.5 MPa. The longitudinal slope of the longwall No. 004z was between 0° and 12°, while the transverse slope was between 0° and 13°. The thickness of the coal seam No. 504 in the 004z longwall panel ranged from 4.8 m to 8.1 m. The coal in seam No. 504 is prone to rock bursts, as evidenced by its uniaxial compressive strength (UCS) of 18.7 MPa. The ability of the coal to accumulate strain energy was one of the factors adversely affecting the risk of rock bursts in the area of longwall 004z. The direct roof of coal seam No. 504 is mainly composed of shales and sandy shales, and sandstone layers are deposited

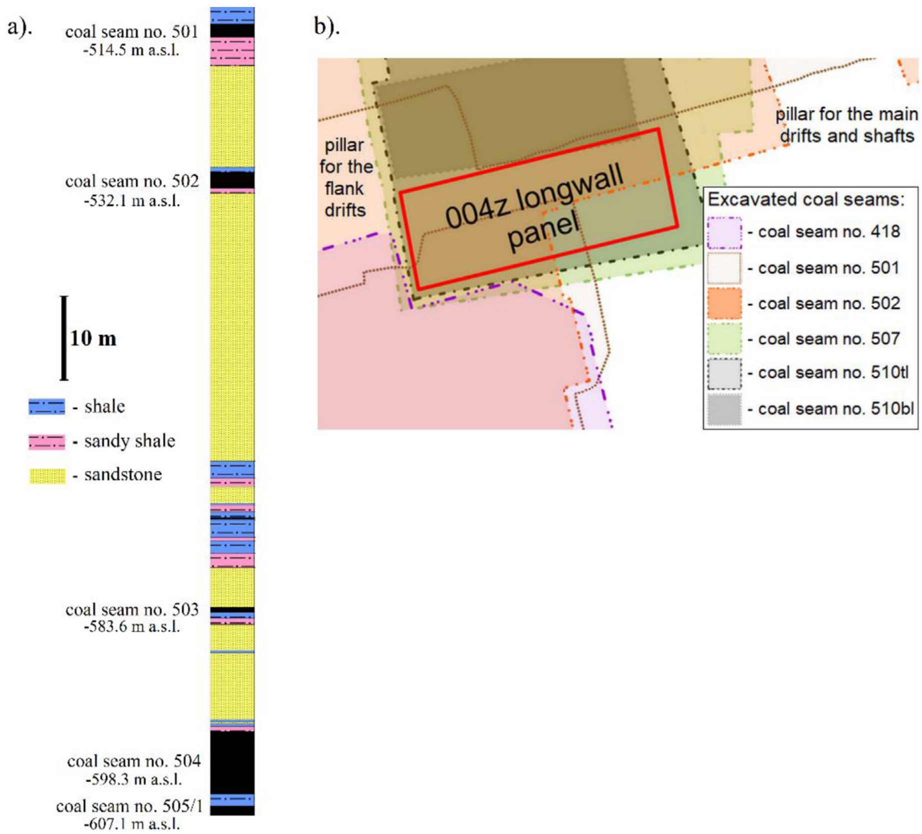

Fig. 1. Geological profile within the 004z longwall panel (a) and previous mining of adjacent coal seams above and below coal seam No. 504 (b).

above them. In the profile of borehole drilled within the 004z longwall panel, the following layers are present in the direct roof of coal seam No. 504 (Fig. 1a): 0.6 m of sandy shale, 0.3 m of shale, 0.2 m of sandstone, 0.3 m of shale, 7.9 m of sandstone, 0.3 m of shale, 3.1 m of sandstone, 0.7 m of sandy shale, 0.7 m of shale, 0.6 m of coal seam No. 503 (non-mineable coal). The total thickness of the sandstones deposited above coal seam No. 504 is 61.6 m (Fig. 1a). These sandstones are characterized by high strength, with UCS of about 80 MPa. The fracturing of sandstone layers was associated with the possibility of strong tremors and the risk of rock bursts of the stroke or stroke-stress type. In the floor of coal seam No. 504 a layer of shale with a thickness of 1.4 m is present, under which the coal seam No. 505/1 with a thickness of 0.3 m is deposited (Fig. 1a). Figure 1a also shows the depth of deposition of coal seam No. 504 and other adjacent coal seams.

Leaving the lower layer of coal seam No. 504 and the presence of low-strength rocks in the floor of this seam were factors that adversely affected the risk of rock bursts in the area of 004z longwall panel. The longwall No. 004z was planned as the first in coal seam No. 504 in this part of the deposit; however, other coal seams belonging to the 400 and 500 series were previously mined here, e.g. coal seams Nos. 418, 501, 502, 507 and top and bottom layers of coal seam No. 510, i.e. 510tl and 510bl, respectively (Fig. 1b).

The mining of the 501 coal seam, deposited at a vertical distance of about 80–100 m above the coal seam No. 504, was performed over the south-western part of the 004z longwall panel. This mining was performed approx. 47 years before the mining of the coal seam No. 504. Coal seam No. 502, deposited approx. 45–65 m above coal seam No. 504 was extracted over the western and northern parts of the 004z longwall panel. The mining of coal seam No. 502 took place about 45 and 28–29.5 years before the mining of coal seam No. 504, respectively. Due to the time that has elapsed since the extraction of coal seams, Nos. 501 and 502, the destress effect was rather absent. On the other hand, the presence of the edges of coal seams Nos. 501 and 502 above the 004z longwall panel could be related to an increased stress level in the rock mass, i.e. both in the coal seam No. 504 and in the sandstone layers deposited above this seam. The edges of the finished exploitation, especially in the adjacent seams, are a factor that very often causes rock bursts [5]. Stress concentration in the vicinity of the seam edges may be observed even several dozen years after the completion of mining works. Coal seams Nos. 507 and 510tl were mined with caving under the 004z longwall panel. Coal seams Nos. 507 and 510 are deposited at a distance of 54–65 m and 60–75 m below coal seam No. 504, respectively. The exploitation of these coal seams took place about 9–10.5 and 4.5–5.5 years before the exploitation of seam 504, respectively. A certain destress effect could be related to the exploitation of these seams, which would be beneficial from the point of view of the risk of rock bursts. Mining in the vicinity of protective pillars often violates the unstable state of strain-stress equilibrium in the rock mass, established as a result of multi-seam exploitation. Reaching a new state of strain-stress equilibrium is associated with the occurrence of strong tremors. Tremors of such a cause were observed during earlier mining of coal seams Nos. 507 and 510 in this part of the deposit [15], and their occurrence could not be ruled out during the planned mining of coal seam No. 504, which was important for safe and effective mining.

3. Seismicity and seismic monitoring

The geological and mining conditions during the mining of the 004z longwall panel in coal seam No. 504 were reflected in the observed level of rock burst hazard, including the recorded seismic activity. The 004z longwall panel was covered by seismic monitoring using the ARAMIS S system. The network consisted of 16 underground seismic stations. Most of the sensors were SPI-70 seismometers, but also low-frequency geophone probes were installed in underground openings. These seismic stations were located at depths ranging from approx. 520 m to approx. 1000 m below the ground level. For the location of tremors, the method of the first arrivals of seismic wave P was used. In the area of longwall No. 004z, the error in determining the epicenter of tremors was in the range 15.4–17 m, while the error of the hypocenter was between 29.5 m and 33.6 m. The energy of the tremors was determined by the numerical integration of seismograms. Moreover, the energy of strong tremors, i.e. with energy 1×10^5 J or higher, was verified with the Upper Silesian Regional Seismological Network of the Central Mining Institute. During the mining of the 004z longwall panel in coal seam No. 504, a total of 2938 tremors (both induced/triggered by mining and provoked by blasting) with a total seismic energy of 1.2×10^7 J were recorded, including 2398 tremors with an energy of 10^2 J, 440 tremors with an energy of 10^3 J, 81 tremors with an energy of 10^4 J (medium energy tremors), as well as 17 strong tremors with an energy of 10^5 J and two strong

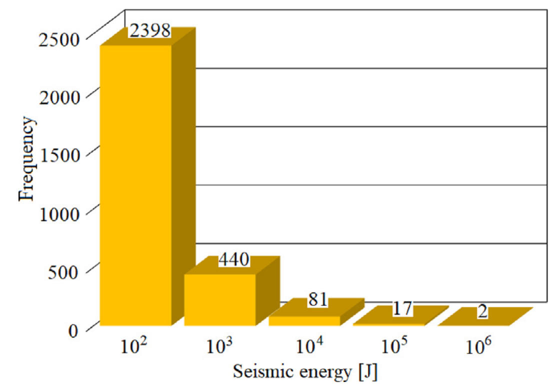

Fig. 2. Seismic activity during mining of the 004z longwall panel in the top layer of coal seam No. 504.

tremors with an energy of 10^6 J (Fig. 2). All strong tremors were caused by the mining, and they were not provoked by blasting.

The epicenters of low and medium-energy tremors were located mainly in the 004z longwall panel. The occurrence of these tremors was related to the destruction processes of coal seam or surrounding rocks. Whereas strong tremors were located both within the longwall panel and in the vicinity of the protective pillars, i.e. to the east and west of the 004z longwall panel (Fig. 3). Nearly half of the strong tremors occurred south of the 004z longwall panel where the edges of the adjacent coal seams were present (Fig. 3). Figure 3 also shows the 2D distribution of cumulative seismic energy. The area of the analyzed longwall panel was divided into cells with dimensions of 50×50 m. The seismic energy of the tremors in each cell was summed. Isolines connecting points with the same value of the sum of seismic energy were generated by the kriging interpolation method.

Determining the reasons for the occurrence of strong tremors was of significant importance for the assessment of the rock burst hazard during the mining of the 004z longwall panel in coal seam No. 504.

Analysis of the mechanism of strong tremors occurring during the mining of the 004z longwall panel was carried out using the seismic moment tensor inversion method.

4. Determination of the focal mechanism of mine tremors

Determination of the mining-induced tremor mechanisms is possible on the basis of targeted analysis of seismograms. Currently, the most widely used model of tremor foci is the model based on the seismic moment tensor. The SMT inversion method

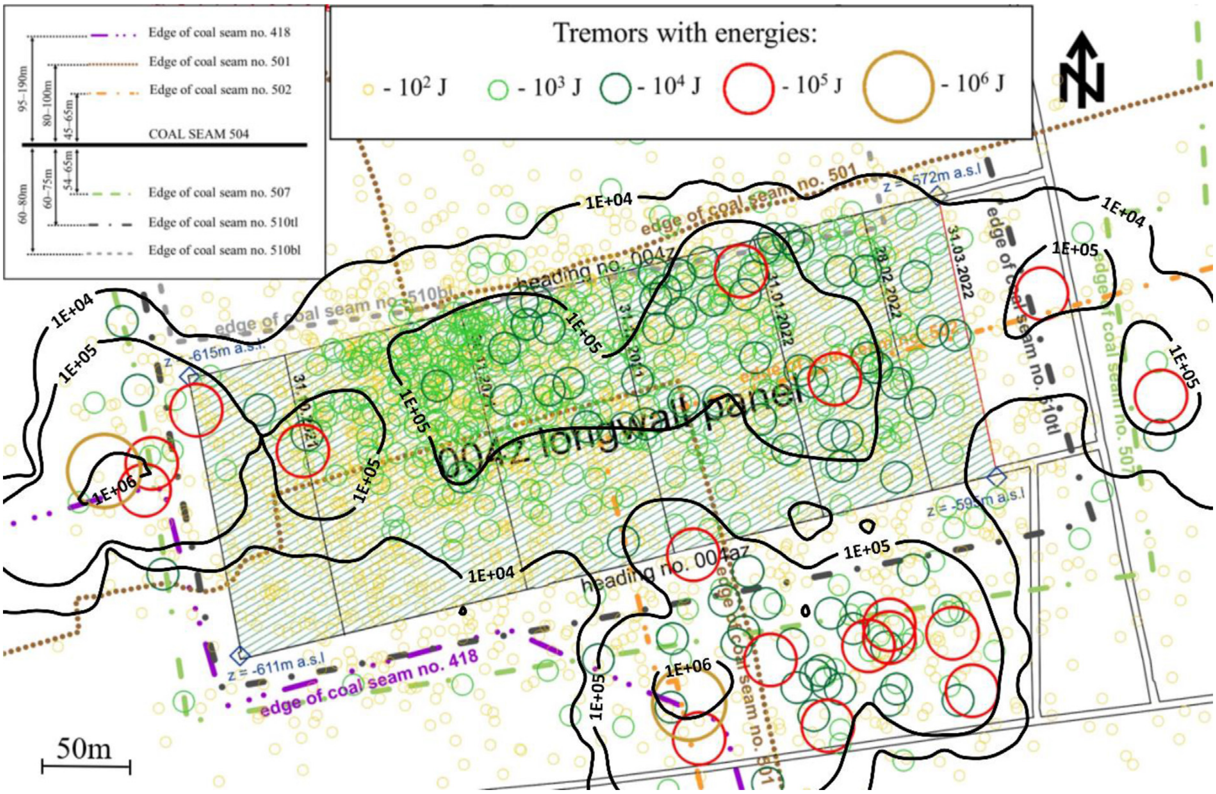

Fig. 3. Map of mining excavations in coal seam No. 504 with seismic activity during mining of the 004z longwall panel.

is used to determine the focal mechanism of tremors. This method was firstly used to study earthquakes [16,17], and then it was adapted to mining seismology [18–27]. Tremors are the result of the action of a specific system of forces on a fragment of the rock mass in which the tremor focus is initiated. The system of forces oriented in space determines the course of dynamic processes defined for it [23]. The processes taking place in the focus are the source of the characteristic seismic radiation. Seismic sources are usually described using models of equivalent forces, generating displacements of the rock mass at a given point identical to displacements caused by real forces acting in the focus [18]. A seismic moment tensor describes a system of forces acting in a seismic source as a linear combination of pairs of forces. In the seismic moment tensor inversion method, it is assumed that the seismic source is point-like, i.e. its dimensions are small in relation to the observed seismic wavelengths. The displacement field caused by the system of forces acting in the source of the tremor is the sum of displacements caused by individual pairs of forces, which can be written as [28]:

$$u_k(x,t) = M_{ij}\frac{dG_{ki}}{dx_j} = M_{ij} * G_{ki,j} \tag{1}$$

where

M_{ij} – moment of the force couple acting in the direction of the x_i axis, with the arm along the x_j axis,

G_{ki} – Green's function (a function describing the impulse response of a rock mass along the path travelled by a seismic wave),

$G_{ki,j}$ – derivative of Green's function after the index following the comma,

$*$ – convolution.

Assuming that all components of the seismic moment tensor undergo the same changes in time, the displacement field can be written as follows:

$$u_k(x,t) = M_{ij}\left[G_{ki,j} * s(t)\right] \tag{2}$$

where $s(t)$ denotes source function (characterizing the seismic emission from the source over time). The source of the tremor is then synchronous, i.e. it causes the same changes in time in all directions. Assuming that the source function is a Dirac's function, the displacement field can be described as follows:

$$u_k(x,t) = M_{ij}G_{ki,j} \tag{3}$$

The set of all components M_{ij} written in the form of a matrix M with dimensions 3×3 represents the seismic moment tensor:

$$\mathbf{M} = \begin{bmatrix} \mathbf{M}_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix} \quad (4)$$

The three diagonal components ($i = j$) describe pairs of forces without moments and are directed along the axis of the coordinate system, respectively, and the remaining six components represent respectively directed moments of force. A graphic representation of the combination of directions and force arms for the seismic moment tensor is shown in Figure 4.

The SMT inversion consists in calculating its components on the basis of the displacement field recorded by the seismological network. When determining the seismic moment tensor, a system of equations is solved containing information on the amplitudes and signs of the first deflections of the recorded seismic waves, as well as the properties of the medium between the tremor and the seismic station and the way of wave propagation in the rock mass. Seismic moment tensor decomposition is used to identify the geomechanical processes taking place at the tremor focus. This tensor can be decomposed into an isotropic component (ISO) and a deviatoric component describing the form change without changing the volume, consisting of a compensated linear vector dipole (CLVD) and a double couple of forces (DC). The isotropic component describes the volume changes in the source uniformly in all directions ("+" explosion or "−" implosion). It concerns the volumetric destruction of the medium's structure (e.g. as a result of blasting). Compensated linear vector dipole corresponds to a mechanism close to uniaxial compression ("−") or tension ("+"). The CLVD component may describe the cracking of pillars. A double couple of forces describes the process of shear and slip. The mechanism described by a double couple of forces corresponds to the tremors associated with the fracturing of compact rocks of high stiffness and strength or the activation of existing faults. As a result of the calculations, three models of the tremor focus are obtained, described by three types of seismic tensor: full (containing the components: ISO, CLVD, DC), deviatoric (containing the components: CLVD, DC) and pure shear (containing only the DC component). In the case of tremors of the rock mass caused by mining, apart from the dominant shear processes on the slip planes, also other focal mechanisms are possible [29]. The decomposition of the seismic tensor into ISO, CLVD and DC components is the most commonly used description of a seismic source [18,20,22,25,27]. In the full solution of the seismic tensor, the percentage share of each of the ISO, CLVD and DC components is determined. In the case of the dominance of the DC shear component, the spatial orientation of the slip plane on which the displacement takes place is determined. The spatial orientation of the fracture plane at the focus is determined graphically. A focal sphere surrounding the tremor hypocenter and spatially oriented in accordance with the direction of the geographical system and vertical is used. Then, the image is transformed from the focal hemisphere to the plane (Fig. 5). Typically, a stereographic projection of the lower focal hemisphere using the Wulff or Schmidt net is used. After the mapping of the focal hemisphere, the areas of compression (P) and dilatation (T) are separated in the projection image. The position of the compression and dilatation areas is determined on the basis of the direction of the first onset of the P wave ("−" or "+") on the seismograms.

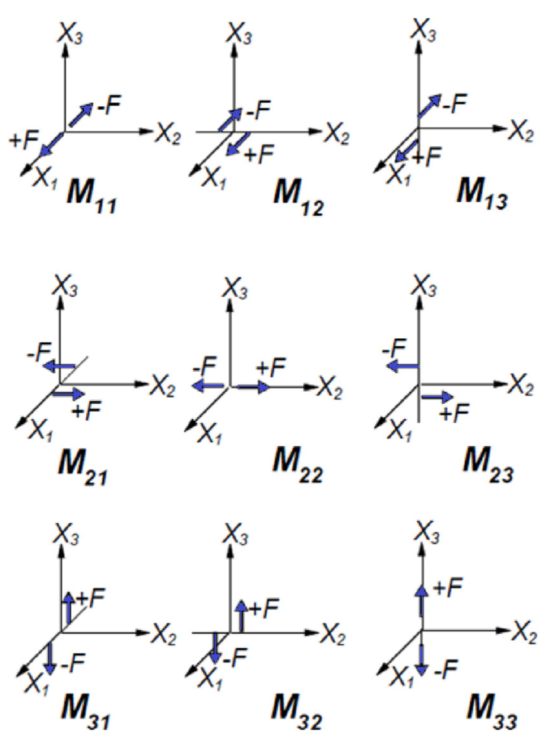

Fig. 4. Nine couples of equivalent forces M_{ij} forming the seismic moment tensor [28].

The angular parameters of the solution of the source mechanism of tremor are calculated. The spatial orientation of the A and B nodal planes separating the areas of compression and dilatation is determined. One of them represents the real fracture plane, and the other is the auxiliary plane (Fig. 5). For each of these planes, its azimuth (Φ) and dip (δ) are determined, and the angle of displacement on this plane, i.e. rake angle (λ) is also determined. It is the angle between the running direction of the nodal plane and the shift direction. It is also

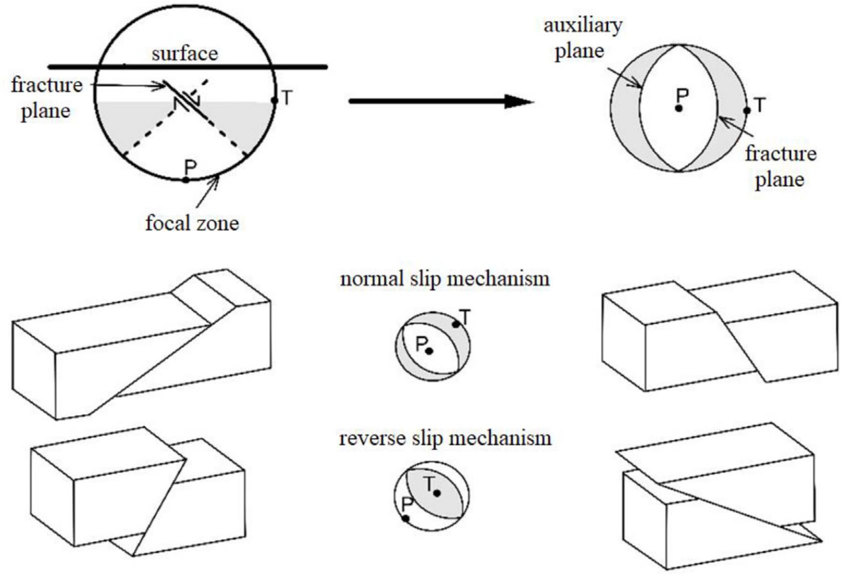

Fig. 5. Graphical representation of focal mechanism ([21], modified).

possible to calculate the parameters of the compression (*P*) and tension (*T*) axes.

5. Results of the full SMT inversion

Based on seismograms recorded by the mine seismological network in the Bielszowice part of the Ruda Hard Coal Mine, the focal mechanisms of high-energy tremors that occurred during the mining of 004z longwall panel in coal seam No. 504 were determined. The calculations of the seismic moment tensor were performed in the FOCI software [30] based on the inversion of the amplitudes of the first arrivals of the P wave, taking into account the directions of the first onsets in the time domain. Based on the mentioned records, focal mechanisms for 17 out of 19 high-energy tremors in the area of the 004z longwall panel were calculated. In the case of two tremors with energy of the order of 10^5 J, the recorded seismograms turned out to be incomplete. The seismic stations were located around the 004z longwall panel (Fig. 6). To determine the SMT, mostly the seismograms from 10 or 11 seismic stations were used. In order to determine the source mechanisms of tremors, the seismic stations located at a horizontal distance of at least more than 500 m from the focus were taken into account (Fig. 6). The purpose of such selection of seismic stations was to reduce the near-field effect. A similar criterion of the focus-sensor distance was adopted for tremors in one of the Chinese hard coal mines [31]. In the vast majority of cases, the shortest horizontal distance of the seismic station from the focus of the tremor was about 700−800 m.

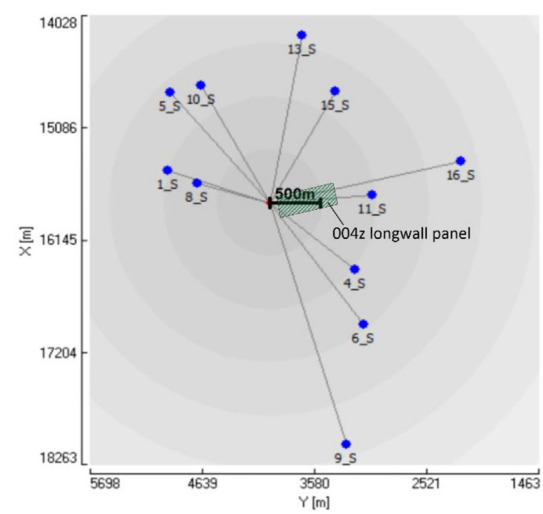

Fig. 6. Arrangement of the seismological network stations in relation to the focus of one of the analysed strong tremors in the area of the 004z longwall panel (based on the FOCI software).

Considering the error of determining the epicenter of tremors in the area of the 004z longwall panel, it was found that the horizontal coordinates of the tremors were determined with sufficient accuracy. On the other hand, the vertical component of tremor foci was recalculated in the FOCI software. The solution of the seismic moment tensor for the highest value of the quality factor and the smallest error in its determination was set as final. The recalculated depths of the tremors' foci differed from the original depths by an average of about 21% (median of about 14%). The L1 norm was used as less sensitive to possible outliers that may be an effect of random noises related to, e.g. works performed in the vicinity of sensors. The calculated parameters of the focal mechanisms of strong tremors are presented in Table 1.

In the foci of all strong tremors, the slip mechanism was dominant, and the DC component ranged from 47.3% to 98.2% (mean 69.5%). Taking into account the depth of the tremor foci determined for the best solution of the seismic moment tensor and the dominance of the shear mechanism in the foci, the source of the tremors were the processes of destruction occurring in sandstones deposited in the direct and main roof of coal seam No. 504. Only in one case (tremor No. 13) the best solution of the SMT was obtained for the depth below the coal seam No. 504. The location and mechanism of strong tremors in the area of the 004z longwall panel are shown in Figure 7.

Strong tremors No. 1 and 2 were probably related to the disturbance of the strain-stress equilibrium being a result of multi-seam mining in the vicinity of the pillar for the flank drifts. Tremor No. 1 with an energy of 1×10^6 J was located in the rock mass where coal seam No. 504 was not mined, to the west of the 004z longwall panel. Tremor No. 2 was located close to the 004z longwall panel, near the longwall start line. The depth for the best solution of the source mechanism, i.e. about 150 m above coal seam No. 504, suggests that the tremor may have been directly related to the edge of coal seam No. 418. The azimuth of the nodal plane A correlated partially with the position of the edge of the coal seam No. 418, but it was closer to the WNW-ESE direction (difference of about 50°). The reverse slip mechanism means that tremor No. 1 was generated in conditions close to horizontal stresses (the main compression axis dip was 39°). In turn, in the case of tremor No. 2, the depth of the best solution of the SMT (about 50 m above coal seam No. 504) suggests a fracture in the sandstones deposited below coal seam No. 502. The azimuth of the nodal plane A coincided with the location of the longwall face and edges of seams Nos. 507 and 510tl. Normal slip mechanism occurred towards the mined coal seam No. 504 and extracted coal seams Nos. 507 and 510tl. The best solution for tremor No. 3 was obtained for a depth of about 60 m above coal seam No. 504, which in this area corresponds to sandstones deposited below coal seam No. 501. The azimuth of nodal plane A clearly correlates with the position of the edge of coal seam No. 418. In the focus of tremor No. 3, there was most likely a normal slip mechanism in the sandstone additionally stressed due to the edge of coal seam No. 418. In turn, in the focus of tremor No. 4 there was a reverse slip mechanism.

Table 1. Parameters of the focal mechanisms of strong tremors in the area of 004z longwall panel.

No.	Coordinates in the Sucha Góra system			Seismic energy [J]	Nodal plane A			Nodal plane B			Share of the components			Type of mechanism[b]
	X [m]	*Y* [m]	*Z*[a] [m]		*Φ* []	*δ* []	*λ* []	*Φ* []	*δ* []	*λ* []	ISO [%]	CLVD [%]	DC [%]	
1	15797	4001	−480	1.0E+06	301.3	84.3	87.6	143.9	6.2	112.6	−2.9	−0.1	97.0	RE
2	15754	3935	−580	3.0E+05	346.7	88.9	−83.7	86.7	6.4	−169.9	−7.6	−33.3	59.1	NO
3	15988	3576	−540	4.0E+05	324.9	84.8	−84.8	99.5	7.3	−135.2	7.9	20.8	71.3	NO
4	15913	3395	−610	2.0E+05	171.9	88.7	72.6	77.7	17.4	175.5	9.5	13.5	77.0	RE
5	15783	3859	−560	3.0E+05	171.5	78.2	87.1	5.3	12.1	103.4	18.8	33.9	47.3	RE
6	15963	3583	−520	1.0E+06	315.5	73.1	−88	128.6	17	−96.6	−13.4	−26.4	60.2	NO
7	15979	3484	−500	3.0E+05	327.4	72.5	−84.1	128.5	18.5	−108	−9.9	−18.1	72.0	NO
8	15792	3967	−580	3.0E+05	21.8	86.3	99.9	132.2	10.6	20.8	−0.2	1.6	98.2	RE
9	15954	3381	−580	5.0E+05	308.1	71.1	87.6	135.7	19	97.1	15.8	24.9	59.3	RE
10	15655	3546	−510	2.0E+05	257.7	77	−91	82.3	13	−85.5	−19.6	−21.5	58.9	NO
11	15744	3246	−510	1.0E+05	337.1	71.6	−88.6	152.5	18.5	−94.3	−4.5	−10.2	85.3	NO
12	15732	3479	−610	2.0E+05	278.5	75.9	−97.3	126.4	15.8	−63.1	−11.9	−28.2	59.9	NO
13	15671	3331	−650	2.0E+05	172.9	86.7	−99.1	63.1	9.7	−20.1	−11.0	−22.1	66.9	NO
14	15916	3440	−480	4.0E+05	355.8	74.1	−86.8	164.4	16.3	−101	−10.3	−22.3	67.4	NO
15	15811	3972	−550	2.0E+05	208.6	86.8	−102.3	104.4	12.7	−14.5	−11.2	−19.6	69.2	NO
16	15907	3440	−510	3.0E+05	339.6	89.4	107.6	71.4	17.6	1.9	−1.6	−17.6	80.8	RE
17	15922	3455	−490	1.0E+05	359.1	77.3	−78.3	135.8	17.2	−132	−16.6	−31.5	51.9	NO

[a] Depth of the foci, recalculated in the FOCI software.
[b] NO – normal slip mechanism, RE – reverse slip mechanism.

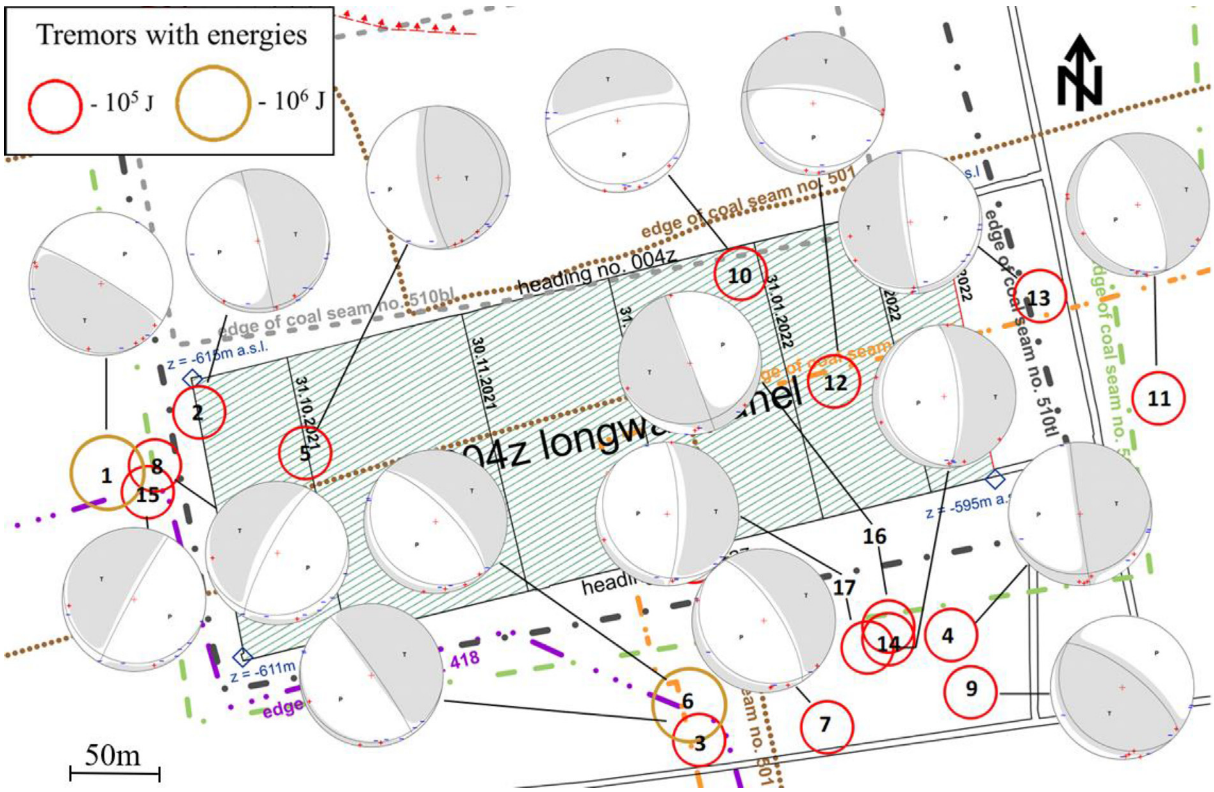

Fig. 7. Distribution and focal mechanism of strong tremors in the area of 004z longwall panel.

The depth of the best solution of the seismic moment tensor corresponded to the depth of coal seam No. 504 in this area. The azimuth of the nodal plane A coincides with the edges of coal seams Nos. 501 and 502, located more to the west. The main compression axis dip was 41°. The reverse slip mechanism was also present in the focus of tremor No. 5. The best solution of the seismic moment tensor was obtained at a depth of about 40 m above coal seam No. 504, which corresponds to sandstones deposited below coal seam No. 502. The azimuth of the nodal plane A corresponds to the longwall face. The dip of the main compression axis was 33°. Normal slip mechanism occurred in the focus of tremor No. 6 with an energy of 1×10^6 J. The focus of this tremor was located at a depth of about 80 m above coal seam No. 504, which may indicate that the source of the tremor was a fracture in the sandstones deposited in the vicinity of coal seam No. 501, additionally stressed due to the presence of the edge of the coal seam No. 418. The azimuth of the nodal plane A coincides with the position of the edge of the coal seam No. 418. A similar mechanism was found in the case of the focus of tremor No. 7, located in the same area and at a similar depth. Tremor No. 8 was located west of the longwall start line and was characterized by the dominance of the reverse slip mechanism (98.2%). The best solution of the SMT was obtained at a depth of about 50 m above coal seam No. 504, which corresponds to sandstones deposited below coal seam No. 502. The azimuth of the nodal plane A correlates to some extent with the position of the edge being a result of the mining of the 004z longwall panel and the edges of the previously mined coal seams Nos. 507 and 510tl, with the difference between them of about 30°. The main compressive stresses occurred along the W–E direction, and the dip of the main compression axis was 40°. The strain-stress equilibrium, created as a result of multi-seam mining in the vicinity of the pillar for the flank drifts, was disturbed. The depth for the best solution of the seismic moment tensor for tremor No. 9 corresponded to sandstones deposited below coal seam No. 502 (about 40 m above coal seam No. 504). In the focus of this tremor, a reverse slip mechanism was present. The dip of the main compression axis was 26°. The azimuths of the nodal planes coincide with the position of the edge of coal seam No. 418. It cannot be ruled out that the tremor could have been affected by the uneven distribution of stresses in the thick sandstone layer, related simultaneously to the influence of the edge of the coal seam No. 501 and the perpendicular edges of the coal seams Nos. 507 and

510tl. Tremor No. 10 occurred in the northern part of the 004z longwall panel, in the area of the edges of coal seams Nos. 510bl and 501. The best solution of the focal mechanism was found at a depth of about 60 m above coal seam No. 504, which in this area corresponds to sandstones deposited below coal seam No. 501. The azimuth of nodal plane A correlates with the position of the edge of coal seam No. 501. Normal slip mechanism was present in the focus of this tremor. Mine tremor No. 11 occurred east of the 004z longwall panel, close to the edge of coal seam No. 507 and in the vicinity of the protective pillar for shafts, where the extraction of coal seams Nos. 412/2 and 414/1 was finished. Vertical distance of these coal seams from the coal seam No. 504 equals approx. 363–397 m and approx. 307–320 m, respectively. The best solution of the SMT was obtained at a depth of about 80 m above coal seam No. 504, which in this area corresponds to sandstones deposited below coal seam No. 501. The azimuths of the nodal planes correspond to the position of the edges of coal seams Nos. 507, 412/2 and 414/1. In the focus of tremor No. 11, the normal slip mechanism occurred. Tremor No. 12 occurred in the 004z longwall panel in the vicinity of the edge of coal seam No. 502. The best solution of the focal mechanism was obtained for the depth of the coal seam No. 504. The azimuth of the nodal plane A correlated with the position of the edge of the coal seam No. 502. Probably, a normal slip occurred in sandstones deposited in the direct roof of coal seam No. 504, additionally stressed due to the impact of the edge in coal seam No. 502. Tremor No. 13 occurred to the east from the 004z longwall panel, in the area of the edge of coal seam No. 510tl. The best solution of the seismic moment tensor was obtained at a depth of about 50 m below coal seam No. 504. Normal slip mechanism occurred in the focus of this tremor. Roof rocks of coal seams Nos. 510tl and 507 (the distance between these seams is only about 10 m in this area) slipped towards the old gobs left by the extraction of coal seam No. 510tl. Thus, a new state of strain-stress equilibrium was established. The azimuth of the nodal plane A correlated with the edge of the coal seam No. 510tl, and the rock displacement was almost vertical towards the old gobs. Tremors Nos. 14, 16 and 17 were located south of the 004z longwall panel, and they were located in close proximity to one another. The depths for which the best solutions of the seismic moment tensor were obtained correspond to the sandstones deposited in the vicinity of coal seam No. 501 (about 90–120 m above coal seam No. 504). The azimuth of the nodal plane A determined for the foci of these tremors correlates with the position of the edge of the coal seam No. 501. In two cases, the normal slip mechanism was found, and in one the reverse slip mechanism was present. Tremor No. 15 occurred west of the longwall panel and, similarly to tremors No. 1, 2 and 8, it was related to a disturbance of the strain-stress equilibrium, being a result of multi-seam mining in the vicinity of the pillar for flank drifts. The azimuth of the nodal plane A differed by about 30° from the position of the edges of the seams Nos. 507 and 510tl, while the azimuth of the nodal plane B correlated with the position of the edge of the seam No. 418. The best solution of the seismic moment tensor was obtained at a depth of about 80 m above coal seam No. 504, which corresponds to sandstones deposited in the vicinity of seam No. 501. The source of this tremor was most likely a fracture and slip in a thick sandstone layer stressed by the edge of seam No. 418.

In the vast majority of the analysed focal mechanisms, the azimuths of nodal planes correlated with the edges of the adjacent coal seams. The main threat came mainly from the rigid and strong rocks, i.e. sandstones, deposited in the roof of coal seam No. 504, additionally stressed in the vicinity of remnants in the previously mined seams. The rock burst prevention for the longwall No. 004z was mainly focused on the destruction of roof rocks of the 504 seam.

6. Rock burst prevention

The first active rock burst prevention was applied during the preparatory works for the longwall No. 004z. It was based on the cyclical long-hole destress blasting in roof rocks from the longwall galleries. One long-hole destress blasting used 96 kg of explosives which were loaded into two blastholes, i.e. 48 kg per hole. The blastholes were 60 m long and inclined to the horizontal at an angle of 60°. Such parameters of the blast holes were aimed at fracturing the layer of sandstone deposited above coal seam No. 503 (Fig. 1a). The goal was to prevent this sandstone layer from accumulation strain energy. It was also important that the fractured and loosened rocks did not add additional load to the support of longwall galleries. The blasting was performed approximately every 50 m. In each pair of blastholes, one was directed to the WNW and the other was directed to the WSW. The selected blasting parameters resulted from obtaining the largest possible range of fracturing in the rock mass and the technical possibilities of drilling blast holes. In total, 23 long-hole destress blasts were performed from longwall galleries during their drilling, i.e. 12 from heading No. 004 and 11 from heading No. 004az (Table 2). By these blasts, tremors with energies

Table 2. Characteristics of long-hole destress blasts in roof rocks for the 004z longwall panel.

Excavation	Number of blasts	Number of blastholes	Total mass of fired explosives [kg]	Total seismic energy of provoked tremors [J]
Heading No. 004z	12	24	1152	1,05E + 05
Heading No. 004az	11	22	1056	5,2E + 04
Heading No. 004az (during mining of 004z longwall panel)	3	6	432	3,8E + 04
Longwall No. 004z	12	36	2592	3,0E + 05

from 2.0×10^3 J to 1.0×10^4 J were provoked. During the long-hole destress blasting from the drilled longwall galleries, a total of 2208 kg of explosives were fired, and the total seismic energy released was 1.57×10^5 J. During the drilling of longwall galleries, seismic surveys were also carried out using the profiling method. The obtained results confirmed the stress level in coal seam No. 504 at a normal level.

After the commencement of mining and after analysing the seismic activity that occurred south of the longwall panel, including the mechanisms of strong tremors (Nos. 3, 4, 6, 7), three long-hole destress blasts were designed and performed, aimed at the destruction of sandstones deposited in the area of the edges of coal seams Nos. 501 and 502 (Table 2). The blastholes were up to 70 m long and inclined to the horizontal at an angle of 60°. The column of explosives was located in the sandstones deposited in the vicinity of coal seam No. 502. The aim was to fracture a thick layer of sandstone between coal seams Nos. 502 and 503 and partially fracture the sandstone deposited below coal seam No. 501 (Fig. 1a). Each time, blast holes were drilled in the south-west and south-east direction, and 144 kg of explosives were fired (72 kg of explosives per hole). These blasts resulted in tremors with energies of 8.0×10^3 J, 1.0×10^4 J and 2.0×10^4 J.

Due to the increase in seismic activity as the 004z longwall face approached the edge of the coal seam No. 502, cyclical long-hole destress blasting from the longwall face was designed, which was then continued until the end of longwall mining. In each case, 216 kg of explosives were loaded into three blastholes 60 m long each (i.e. 72 kg of explosives per hole). Blastholes were drilled perpendicular to the longwall face and inclined to the horizontal at an angle of 60°. The column of explosives was located in the sandstones deposited above coal seam No. 503. The parameters of the blasting resulted from obtaining the greatest possible destress effect in front of the longwall face and from the technical possibilities of drilling and charging and not disturbing the technological process of mining. In total, 12 such long-hole destress blasts were performed from the longwall face, during which a total of 2592 kg of explosives were fired (Table 2). As a result of these blasts, tremors with energies from 1.0×10^4 J to 4.0×10^4 J were provoked.

The deposition of rigid sandstone in the direct roof of the coal seam No. 504 was related to the local roof overhangs in the area of the crossing of the longwall face with heading No. 004z. A fracture in a thick layer of sandstone in the immediate vicinity of the mentioned crossing could be associated with the occurrence of a stroke or stroke-stress rock burst. This situation was also unfavourable due to the methane and spontaneous combustion hazards. Additional blasts were carried out behind the longwall face to prevent the occurrence of roof rocks overhangs. The location, number of blastholes and the mass of the fired explosives were variable and adapted to the current mining conditions. Each time, 1 to 3 blastholes up to 25 m long were drilled, and 24 kg of explosives were loaded into each hole. In total, 37 blasts were performed to cause caving of roof rocks, and the energies of provoked tremors ranged from 2.0×10^3 J to 2.0×10^4 J. The total

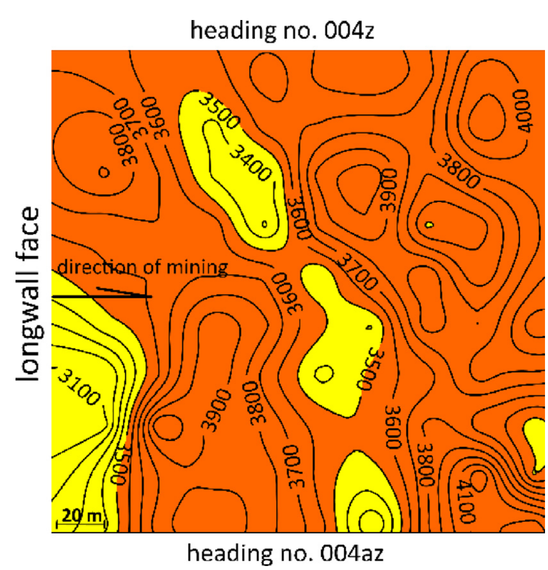

Fig. 8. The distribution of the P-wave velocity in the surrounding rocks obtained during one of the seismic tomographies in the 004z longwall panel.

seismic energy released as a result of these blasts equalled 2.74×10^5 J.

During the mining of the 004z longwall panel, systematic surveys of the stress level in the coal seam No. 504 and the surrounding rocks were carried out. Seismic tomography was applied for this purpose. In total, four seismic surveys of this type were carried out, i.e. before the start of longwall mining and when the longwall face advance equalled approx. 150 m, 300 m and 450 m. Seismic tomography was carried out each time up to 200 m in front of the longwall face. Calculated velocities of P wave propagation in coal seam No. 504 ranged from about 1460 m/s to about 2260 m/s. On most of the 004z longwall panel, the velocities of the P wave in the coal seam No. 504 indicated that the stress level was characteristic of the depth of deposition. Locally, areas where stress drop occurred (with lower P wave velocity) were also found. The occurrence of these areas may have been related to the destress effect coming from the extraction of coal seams Nos. 507 and 510tl and the performed rock burst prevention. As a result of seismic surveys, a low and medium stress increase was also found in coal seam No. 504, which usually occurred close to the longwall face and was correlated with the mining pressure. The velocities of the P wave in the rocks surrounding coal seam No. 504 ranged from about 3060 m/s to about 4490 m/s. The surrounding rocks were mostly moderately prone to causing roof tremors (propagation velocity of the P-wave ranged between 3500 m/s and 4500 m/s), although locally, they were close to the criterion of a strong prone to causing roof tremors. Rocks characterized by the propagation velocity of the P-wave higher than 4500 m/s are strongly prone to causing roof tremors [32]. There were also zones where the surrounding rocks were slightly prone to causing roof tremors (propagation velocity of the P-wave ranged between 2500 m/s and 3500 m/s). The occurrence of these zones could be related to the conducted active rock burst prevention, precisely the long-hole destress blasting, and the destruction of the rock mass due to the occurrence of high-energy tremors and active rock burst prevention during the earlier exploitation of coal seams Nos. 507 and 510tl. The distribution of

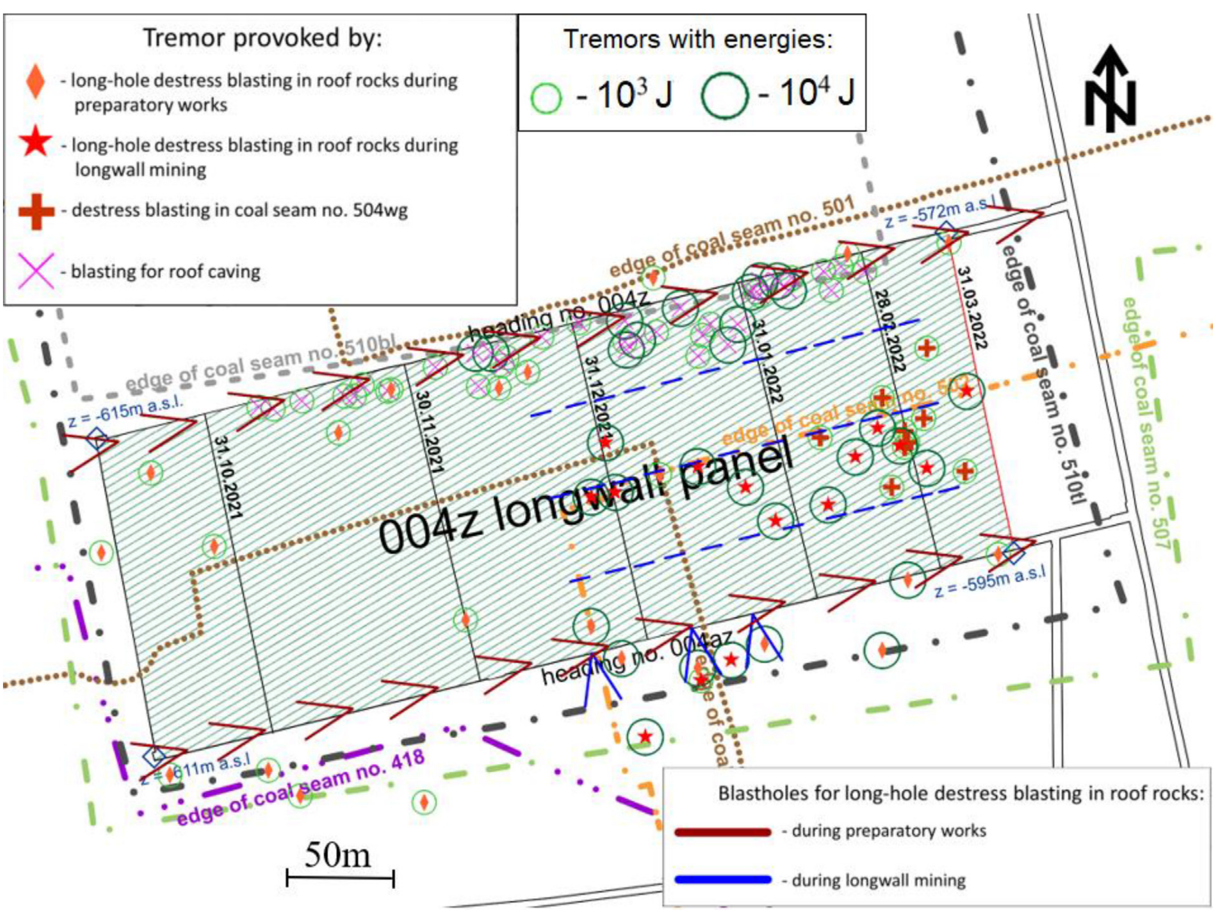

Fig. 9. Tremors provoked by blasting being a part of rock burst prevention for the 004z longwall panel and the location of blast holes during long-hole destress blasting in roof rocks.

the P-wave velocity [m/s] in the surrounding rocks obtained during one of the seismic tomographies in the 004z longwall panel is shown in Figure 8.

Taking into account the results of seismic tomography and the observed seismic activity in the area of the longwall No. 004z, as well as the results of monitoring of the stress rock burst hazard, additional destress blasting in coal seam No. 504 was designed. During each destress blasting, 54 kg of explosives were fired in 9 blast holes (i.e. 6 kg of explosives per hole). The length of the blast holes was 12 m. In total, nine destress blasts were carried out from the longwall face, which provoked tremors with energies from 3×10^3 J to 6×10^3 J. The total mass of explosives fired during these blasts was 486 kg, and the total seismic energy released equalled 3.6×10^4 J.

Tremors provoked by all types of blasting (long-hole destress blasting in roof rocks, destress blasting in coal seam and blasting for roof caving) performed as part of active rock burst prevention for the 004z longwall panel are shown in Figure 9. Additionally, the arrangement of blast holes for long-hole destress blasts in roof rocks fired during the drilling of longwall galleries and during the mining of the 004z longwall panel is also shown.

7. Discussion and conclusions

The mining of 004z longwall panel in coal seam No. 504 was carried out in complex conditions, which included, among others, a large depth, the presence of thick sandstone layers in the direct and main roof of the coal seam No. 504, the occurrence of edges in the adjacent coal seams, the vicinity of protective pillars, thickness of coal seam No. 504 and leaving the lower layer of seam No. 504 in the bottom, as well as proness of coal seam No. 504 to rock burst. To some extent, the exploitation of coal seams Nos. 507 and 510tl was a favourable factor, but the distance of these seams from the coal seam No. 504 (i.e. 54–65 m and 60–75 m, respectively) and the time that elapsed from their extraction (i.e. about 9–10.5 and 4.5–5.5 years, respectively) influenced the degree of destress effect of the seam 504.

The longwall No. 004z was the first in the top layer of coal seam No. 504 in this part of the mine. For this reason, a wide range of passive and active methods of rock burst prevention have been used, e.g. SMT inversion method, seismic tomography, long-hole destress blasting in roof rocks, destress blasting in seam, blasting for roof caving. Proper design of active rock burst prevention requires an analysis of geological and mining conditions and the results of current observations, e.g. mining seismology or in situ seismic surveys. Seismic activity in the area of longwall 004z was maintained at a high level, including high-energy tremors in the rock mass.

In addition to standard analyses related to the seismic activity induced by the mining of longwall panel No. 004z, the study of the focal mechanism of strong tremors was applied and the seismic moment tensor inversion method was used for this purpose. The most probable processes occurring in the tremor foci were determined. The depth of tremor foci was recalculated, and the obtained solutions were characterized by the lowest error and the highest quality factor. The determination of the source mechanisms allowed us to characterize the processes taking place in the foci of strong tremors induced or triggered by mining and to define the dominant factors influencing their occurrence. The occurrence of high-energy tremors was mainly related to the processes of fracture and slip in the thick layers of sandstone deposited in the direct or main roof of coal seam No. 504. Normal slip mechanism dominated in the foci of strong tremors (approx. 65% of cases), and the presence of a reverse slip mechanism was also found (approx. 35% of cases). The edges of adjacent coal seams and the uneven stress distribution in their vicinity played a significant role in generating strong tremors of the rock mass. The azimuths of the calculated nodal planes correlated significantly with the position of the coal seam edges. The results of investigating the mechanisms of strong tremors, together with the results of seismic studies and other methods of observing the state of rock burst hazard, were taken into account in determining the scope and parameters of active rock burst prevention during the mining of the 004z longwall panel. Active rock burst prevention was aimed at the destruction of the roof rocks of coal seam No. 504. About 89% of the blasts for the 004z longwall panel were made in the roof of coal seam No. 504. Almost half of them were the long-hole destress blasts, and the rest were aimed at preventing the local roof overhangs behind the longwall face. Destress blasting in coal seam No. 504 accounted for only about 11%.

About 80% of the strong tremors occurred outside the 004z longwall panel. Mining of the 004z longwall panel disturbed the strain-stress equilibrium state established in the rock mass as a result of previous multi-seam mining. Despite the presence of coal seam edges above the 004z longwall panel, strong tremors occurred sporadically within it.

Mining of coal seams in complex conditions requires the use of a wide range of analyses, e.g. SMT inversion method, seismic tomography, and directed preventive measures, e.g. long-hole destress blasting in roof rocks, destress blasting in coal seam, blasting for roof caving. The method of seismic moment tensor inversion may prove useful in determining the processes responsible for the occurrence of strong mining tremors. Understanding such processes makes it possible to focus rock burst prevention on limiting the causes and/or effects of strong tremors. Rock burst prevention based on long-hole destress blasting in roof rocks is of great importance during coal seam mining under a thick layer of sandstone.

Extraction of the 004z longwall panel in the Bielszowice part of the Ruda Hard Coal Mine was completed in accordance with the design assumptions. The risk of rock bursts did not constitute a barrier to achieving the assumed extraction of hard coal from the 004z longwall panel.

Conflicts of interest

The authors declare no conflict of interest.

Ethical statement

The authors state that the research was conducted according to ethical standards.

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