Publikacja 7

RaSiM 7(2009): Controlling Seismic Hazard and Sustainable Development of Deep Mines, C.A. Tang(ed), Rinton Press, 415-426

CHARACTERISTICS OF THE PROCESSES TAKING PLACE AT THE SOURCES OF HIGH ENERGY TREMORS OCCURRING IN THE UPPER SILESIAN COAL BASIN IN POLAND – REGIONAL CHARACTER OF THE PHENOMENON

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Seismic observations in the Upper Silesian Coal Basin carried out by the Upper Silesian Regional Seismic Network of Central Mining Institute date back to the 1950s. More than 61 000 mine tremors of energy E $\geq 10^5$ J (local magnitude $M_L \geq 1{,}6$) occurred over the period of 1974 to 2008. From the analysis of the seismic source location relative to mine faces and from the analysis of the tectonic structures location, two types of seismicity have been distinguished. These are called respectively mining and regional types of seismicity. The former one is strongly associated with the mining activity and seismic events that occur in the vicinity of active mining excavations. These events are, as a rule, energetically relatively weak. The latter one results from the interaction between mining and tectonic factors. These seismic events appear to be located in tectonically disturbed zones (faults) and the sources are visibly more energetic. They can also be intensely felt on the surface.

1 Introduction

Mining exploitation in the Upper Silesian Coal Basin conducted since more than 200 years causes equilibrium disturbance in the stress field distribution in the rock medium. The symptoms of this disturbance constitute dynamic phenomena in the form of rock mass tremors and rockbursts. The first documented mine tremor registrations originate from the beginnings of the 20^{st} century [15]. In 1929 the first seismic station was established in Racibórz. Over the period 1929 – 1944 in the area of the Upper Silesian Coal Basin five seismic stations were active, with optical registration in the framework of the so-called regional system. In 1965 a seismological station at the first mine started and since this time systematic increase in the number of mine stations, up to 43 maximally in 1980s, was observed. Parallel with the development of mine networks the regional network was modernised. Seismic observations in the Upper Silesian Coal Basin carried out by the Upper Silesian Regional Seismic Network of the Central Mining Institute date back to the 1950s. More than 61000 mine tremors of energy E $\geq 10^5$ J (local magnitude $M_L \geq 1.6$) occurred over the period of 1974 to 2008. The intensity level of seismic phenomena is very differentiated, from non-perceptible to the people to strong ones having the character of weak earthquakes (seismic energy E $\geq 10^9$ J, $M_L \geq 4.0$).

The majority of tremors in the Upper Silesia constitute pure mining-related tremors connected with the change of the system of stresses and deformations caused by direct extraction. These are tremors of low or medium seismic energy value ($10^2 \div 10^7$ J, $M_L = 0.1 \div 2{,}7$). The focus of these phenomena occurs within the fronts of mined longwalls [7, 10, 11, 14].

Every few months, tremors of so-called regional character occur; their seismic energy is high, of the order of $10^8 - 10^9$ J, their focus are connected with geological-tectonic structures and accompanying them zones of natural stress concentrations and rock mass weakness in the form of different types of defects. This activity is caused by changes of the stress system resulting from summing up of residual and neotectonic stresses with stresses caused directly by underground mining [12, 16, 17].

Seismic tremors originate as a result of action of determined forces on the rock medium structure, what causes the characteristic development of dynamic processes and finds its reflection in the character of seismic radiation and indirectly in seismograms of registered tremors. The rock fracturing process can be determined on the basis of parameters describing the focal mechanism, calculated using the seismic moment tensor inversion method [1]. The results of hitherto realised investigations into the focal mechanism allowed to determine more precisely the variability of tremor focal mechanism according to the tectonic features of the region, position of tremor focus towards the longwall front and existing mining events [4, 6, 7, 9, 10, 11, 12, 14, 16, 17].

The parameters, which also describe broader the geomechanical processes occurring in the tremor focus, are source parameters calculated after the assumption of an appropriate model. One of the simplest and simultaneously most often used models is the Brune's model [2]. The simultaneous analysis of focal mechanism parameters and source parameters allows to indicate the characteristic features of tremor focus and thus to give the most probable hypothesis of their reasons.

2 Analysis of high-energy tremors of regional character from the "Bobrek" colliery

In 2007 and 2008 under the city of Bytom occurred two high-energy tremors: the first tremor of 9 February 2007, 2.45 p.m. of seismic energy E = 1.0E+09 J (M_L = 3.8) and second of 12 December 2008 with energy E = 7.0E+08 J (M_L = 3.7). These tremors have not caused effects in the workings of the mined longwall 1 in seam 503 in the "Bobrek" mine, but simultaneously have caused slight damages in several dozen of buildings in Bytom (falling of single roof tiles and damages of chimneys) and were strongly felt in a large area (within the radius up to 12 km).

In order to investigate the character and genesis of these tremors a number of geophysical analyses were carried out. For this purpose seismograms obtained on the basis of registrations of the mine seismological network of "Bobrek" mine and Upper Silesian Regional Seismological Network of Central Mining Institute as well as questionnaire of macroscopic feelings of tremors in the area of Upper Silesia were used.

2.1. Source mechanism

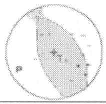
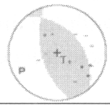
In using the method of mine tremor source mechanism determination we can establish the type of process responsible for the mine tremor source mechanism. As a result of calculations we determine three tremor focus models described by three types of seismic moment tensor [13]:

- the total tensor possesses the isotropic component I describing the source volume variations (explosion /+/ or implosion /-/, CLVD component corresponding with uniaxial compression /-/ or tension /+/ and DBCP shearing component described by a double pair of forces,
- the deviatoric tensor (change of form without volume change) has a CLVD component and DBCP shearing component,
- the pure shearing tensor possesses only the CBCP component – a shearing one.

The accuracy of source mechanism determination was controlled using the solution quality factor Q defined by Wiejacz [13], calculated for each mine tremor being studied. This index, Q, depends on: the source sphere coverage; a coefficient defining the shear solution approximation; and the error of the scalar seismic moment determination. The Q index ranges from 0 to 100%. The results for $Q < 40\%$ have been discarded. The source mechanism is presented as a lower-hemisphere projection with the shaded and white regions indicating compression and dilatation, respectively.

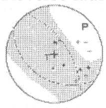
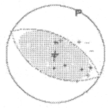
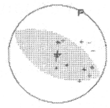
The seismic moment tensor inversion method has been applied to mine tremors from the "Borek" coal mine for two high-energy tremors. Calculations of the seismic tensor moment have pointed out that in the solution decidedly dominated the shearing component over explosion and uniaxial compression. The Tables 1, 2 present the calculation results.

Table 1. Parameters of source mechanism of the tremor of 9 February 2007 from “Bobrek”

Date			Time			Energy, J			Coordinates, m (SG system)		
2007-02-09			14:45			1.0E+09			6420		50
Full solution Reverse fault 				Deviatoric solution Reverse fault 				Double couple solution Reverse fault 			
M_{ij}, Nm				M_{ij}, Nm				M_{ij}, Nm			
-0,295E+13	-0,892E+14	-0,192E+14		-0,333E+14	-0,941E+14	-0,128E+14		-0,379E+14	-0,922E+14	-0,139E+14	
-0,892E+14	-0,165E+15	0,808E+14		-0,941E+14	-0,162E+15	0,823E+14		-0,922E+14	-0,158E+15	0,815E+14	
-0192E+14	0,808E+14	0,191E+13		-0,128E+14	0,823E+14	0,196E+15		-0,139E+14	0,815E+14	0,196E+15	
M_o' Nm		M_T' Nm		M_o' Nm		M_T' Nm		M_o' Nm		M_T' Nm	
0,193E+15		0,216E+15		0,218E+15		0,221E+15		0,218E+15		0,218E+15	
I, %	CLVD, %	DBCP, %		I, %	CLVD, %	DBCP, %		I, %	CLVD, %	DBCP, %	
-3	-6	91		-	-2	98		-	-	100	
ΦA, °	δA, °	ΦB, °	δB, °	ΦA, °	δA, °	ΦB, °	δB, °	ΦA, °	δA, °	ΦB, °	δB, °
171	56	320	38	166	56	319	38	165	56	318	38
ΦP, °	δP, °	ΦT, °	δT, °	ΦP, °	δP, °	ΦT, °	δT, °	ΦP, °	δP, °	ΦT, °	δT, °
248	9	127	72	244	9	120	74	244	9	119	74
Q, %		ERR, Nm		Q, %		ERR, Nm		Q, %		ERR, Nm	
55		0,185+14		62		0,184+14		68		0,185+14	

M_{ij} – seismic moment components, M_o – scalar seismic moment, M_T – full seismic moment, I – percentage share of isotropic component, CLVD – percentage share of component corresponding with uniaxial compression /-/ or tension /+/, DBCP – percentage share of shearing component, ΦA,B – azimuth of plane A,B, δA,B – dip of plane A,B, ΦP,T – trend of axis P,T, δP,T – plunge of axis P,T, Q – coefficient of solution quality, ERR – tensor error

Table 2. Parameters of source mechanism of the tremor of 12 December 2008 from “Bobrek”

Date			Time			Energy, J			Coordinates, m (SG system)		
2008-12-19			23:45			7.0E+08			6620		-380
Full solution Reverse fault 				Deviatoric solution Reverse fault 				Double couple solution Reverse fault 			
M_{ij}, Nm				M_{ij}, Nm				M_{ij}, Nm			
0,558E+14	-0,311E+15	-0,100E+15		-0,836E+15	-0,401E+15	-0,140E+15		-,820E+15	-0,430E+15	-0,134E+15	
-0,311E+15	-0,331E+14	-0,324E+15		-0,401E+15	-0,281E+15	-0,675E+14		-0,430E+15	-0,226E+15	-0,680E+14	
-0,100E+15	-0,324E+15	-0,954E+14		-0,140E+13	-0,675E+14	0,112E+16		-0,134E+15	-0,680E+14	0,105E+16	
M_o' Nm		M_T' Nm		M_o' Nm		M_T' Nm		M_o' Nm		M_T' Nm	
0,814E+15		0,818E+15		0,106E+16		0,109E+16		0,317E+14		0,317E+14	
I, %	CLVD, %	DBCP, %		I, %	CLVD, %	DBCP, %		I, %	CLVD, %	DBCP, %	
10	3	87		-	9	93		-	-	100	
ΦA, °	δA, °	ΦB, °	δB, °	ΦA, °	δA, °	ΦB, °	δB, °	ΦA, °	δA, °	ΦB, °	δB, °
326	58	123	34	297	50	118	41	298	50	118	40
ΦP, °	δP, °	ΦT, °	δT, °	ΦP, °	δP, °	ΦT, °	δT, °	ΦP, °	δP, °	ΦT, °	δT, °
47	12	270	73	28	4	204	86	28	4	206	86
Q, %		ERR, Nm		Q, %		ERR, Nm		Q, %		ERR, Nm	
62		0,708+14		68		0,717+14		69		0,747+14	

The focal mechanism of these tremors is reverse. The nodal planes have azimuth NW–SE. The main compressing stresses P are almost horizontal and have an azimuth close to the direction NE–NW, and the tension stresses T are close to the vertical and have an azimuth corresponding with the direction NW–SE. When analysing the focal mechanism of these tremors from the aspect of investigations conducted by Teper [12] concerning the seismotectonic model of the northern part of the Upper Silesian Coal Basin we can ascertain that the system of stresses acting in the tremor focus and stresses determining the state of rock mass deformations formed during the youngest orogenesis, resulting from the structural analysis, are characterised by natural similarity. Namely, as it is visible from Figure 1 presenting the stress model of UPCB, the direction for compression stresses P corresponds with the direction of compression C, and the direction of stresses T corresponds with the direction of tension T. Moreover, the direction of reverse faults is close to the azimuths of nodal planes determined in focus mechanism solution.

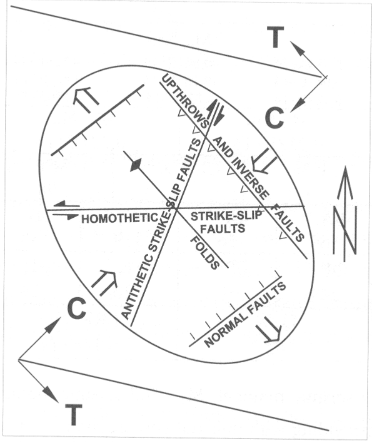


Figure 1. Schematic representation of spatial distribution of deformation complex characteristic for the regime remaining from the Upper Carboniferous through Alpine phases to contemporary movements in the Upper Silesian Coal Basin in the western part of the investigation area (block tectonics zone) and arising in the eastern part of investigations (fold-block tectonics zone) in the Alpine, neotectonic and contemporary stress field [12]

Taking into consideration the relationships presented above we can hypothetically conclude that the solution of the mechanism of focus reflects the system of residual or neotectonic stresses occurring in deep structures of the Upper Silesian Coal Basin. The confirmation of dependences of strong seismic phenomena occurrence on the tectonic factor presents the publication based on ten-years' investigations comprising seismic activity, tectonics and geodynamics of the Upper Silesian Coal Basin area and mining exploitation parameters [16, 17]. As the main contemporary seismogenic structure were acknowledged the discontinuities of the crystalline base running subparallel to boundary zones of the second order between segments of the Upper Silesian massif called blocks: Tarnowskie Góry, Bytom and central block. In the north this is the discontinuity under the Bytom syncline axis.

2.2. Source parameters

The seismic source parameters illustrate the characteristic features appearing in tremor focus. The calculations of parameters of the tremor source of 9 February 2007 and the tremor of 12 December 2008 were carried out using the MULTILOK programme developed in the Laboratory of Seismology and Seismic Prospecting of the Central Mining Institute. The source parameters on account of full not re-controlled record were determined from the seismogram of tremor registered by the Upper Silesian Regional Seismological Network. From the displacement courses the amplitude spectrum was calculated and on the flat part of the spectrum the spectral level Ω_0 and the point of crossing of the flat and inclined part determining the corner frequency f_0 (Fig. 2) were determined.

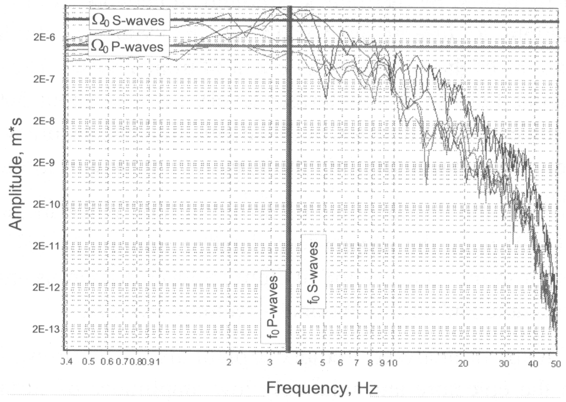


Figure 2. Ground displacement spectrum of the 9 February 2007, 2.45 p.m. of seismic energy E = 1.0E+09 J ($M_L = 3.8$) mine tremor with the low frequency level and corner frequency indicate (blue colour – S-waves, red colour – P-waves)

The results of source parameter calculations presents Table 3.

Table 3. Source parameters

Date	Time	Energy, J	Source parameters					
			M_0, Nm	R_0, m	f_o, Hz	$\bar{D}$, m	$\Delta\sigma$, Pa
2007-02-09	14:45	1.0E+09	4.7E+14	185	3.6	1.2E-02	2.4E+07
2008-12-12	23:45	7.0E+08	8.5E+14	228	4.5	9.9E-02	3.1E+07

M_0 – seismic moment, f_o – corner frequency, R_0 – focus radius, $\Delta\sigma$ – stress drop, $\bar{D}$ – average displacement in the focus

The obtained values of source parameters for the analysed tremors indicate the regional character of these phenomena. The corner frequency (frequency at which the maximum seismic energy is emitted) is low. As a rule for typically mining-related tremors the corner frequency is decidedly higher. The seismic moment is a very high moment as for tremors from the Upper Silesian Coal Basin area. The focus radius is a very high too. The displacement in the focus was exceptionally high. The high drop of stresses in the tremor focus, which manifests the high concentration of initial stresses in the focus area. High displacement in the focus and a high seismic moment are characteristic for tectonic tremors of regional character. Summing up, the large size of the tremor focus, considerable decrease of stresses in the focus and very high seismic energy in the focus indicate that these tremors could not occur at a distance lower than 500-1000 m from the underground workings of longwall 1 in the seam 503, because they would cause the destruction of these workings.

2.3 Spatial location of focus tremors

For the determination of the genesis of tremors very essential is to define the depth of their focus. Calculations of the focal mechanism were carried out for the depth interval from -200 to -1200 m above sea level (from -480 m to -1480 m counting from the terrain surface). The best solution determined on the basis of analysis of the Quality index Q of the solution and lowest error ERR were obtained for the depth 1280 m counting from the surface level, i.e. over 500 m under the occurrence level of seam 503 in the longwall 1 area.

The location in the spatial system has been carried out also by means of the MULTILOK programme. The option was used allowing to localise tremors in the 3D system, modified by the Powell's method. For location the seismogram of tremor registered by the mine seismological network of the "Bobrek" colliery was used. The depth of seismometric stations is differentiated from -300 to -900 m, counting from the terrain level, what allows to carry out calculations of the vertical component of tremor focus. The obtained result indicates that the focus depth amounts to about 1250 m (below terrain level), i.e. also about 500 m under the seam 503. To be sure, seismometric stations were not at disposal at this depth, thus the accuracy of location is limited, but at the spatial network to the level -900 m most certainly the tremor must have occurred decidedly below 1000 m.

Deep, strong tremors from the Bytom syncline area that took place in the 1950s of the previous century (deeper than the mining level) were the subject to a detailed analysis by [3]. It became evident that after the installation of instruments for tremor registration in Upper Silesia, numerous and weaker mining-related tremors could be separated from sporadic and strong regional – tectonic tremors.

The deep position of focus of analysed tremors explain also their strong feelings in a big area within the radius of 10-15 km from the epicentre and relatively low amplitudes of surface vibration acceleration in the tremor epicentre as for such a high seismic energy (about 600 mm/s^2). In the case of weaker and shallower mining-related tremors more than once in the epicentral area an acceleration impulse with higher amplitude (even up to 1000 mm/s^2) was registered. Such impulse is registered in the case of shallow tremors, in a small area around the epicentre, and then it is subject to strong suppression and at the distance of several km in general it is not felt.

It results from macroeconomic questionnaires carried out that the maximum tremor intensity from macroscopic observations according to the MSK scale amounted in the epicentre to $I_0 = 6$, and at the distance of 2.5 km from the epicentre the intensity $I_0 = 4$. Using the formula for vibration intensity with the distance and depth:

$$I_o - I = 3\log\left[(r^2 + h^2) / h^2\right] \quad (1.)$$

where: h – focus depth, r – distance from the epicentre

and after the acceptance of macroscopic data we obtain for the depth 1250 m from the earth surface $I_0 = 4^{th}$ degree (2.5 km from the epicentre) – result accordant with macroseismic observations.

However, in the case of acceptance of the hypothetical focus depth at the level of the mined seam 503 – (750 m from earth surface) the intensity at the distance of 2.5 km from the epicentre can be determined on the boundary of the second and third degree. This result absolutely does not coincide with macroseismic observations, what constitutes the subsequent proof confirming the tremor focus depth, considerably higher than the level of the mined seam 503, and at the same time its regional character.

3 Source mechanism of the mine tremors occurring in the vicinity of local tectonic structures from the „Knurów" colliery

3.1. Focal mechanism

The subsequent examples of tremors, which originated at overlapping of mining-related and tectonic stresses were the tremors that occurred at the "Knurów" colliery in the area of longwall 17 mined in the seam 361. The Tables 4 – 7 present specifications of seismological parameters of analysed tremors and calculation results of mechanism parameters. The three first tremors for full solution of the seismic moment tensor were characterised by reverse slide mechanism with very high share of the shearing component. The focus of tremor of 12 September 2007 for full solution contained 11% of explosive component, 17% of uniaxial tension component and 71% of shearing component (Table 4). The second tremor of 26 October 2007 for full solution was characterised below 1% of the explosive component, 11% of uniaxial tension component and 89% of shearing component (Table 5). The tremor of 7 November 2007 for full solution has pointed out also 86% of the shearing component. The remaining components amounted to: 7% explosive component and 7% uniaxial tension component, respectively (Table 6). The focus mechanism of tremor of 29 November 2007 was of normal slide type. The share of the shearing component was 80%, implosive component 8% and uniaxial compression component 12% (Table 7).

Table 4. Source mechanism parameters of the 12th September 2007

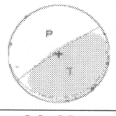
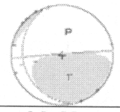
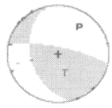
Date			Time			Energy, J			Coordinates, m (SG system)		
12.09.2007			5:53			$1\cdot10^7$			22521		10883
Full solution Reverse fault				Deviatoric solution Reverse fault				Double couple solution Reverse fault			
											
M_{ij}, Nm				M_{ij}, Nm				M_{ij}, Nm			
0,79E+09	0,79E+09	0,79E+09		-0,57E+14	-0,22E+15	-0,77E+15		-0,22E+15	-0,25E+15	-0,35E+15	
0,79E+09	0,79E+09	0,43E+15		-0,22E+15	-0,67E+14	0,12E+15		-0,25E+15	-0,94E+14	-0,28E+13	
0,79E+09	0,43E+15	0,13E+16		-0,77E+15	0,12E+15	0,12E+15		-0,35E+15	-0,28E+13	0,22E+15	
M_o· Nm 0,10E+16		M_T · Nm 0,14E+16		M_o· Nm 0,75E+15		M_T · Nm 0,81E+15		M_o· Nm 0,56E+15		M_T · Nm 0,46E+15	
I, % 11	CLVD, % 18	DBCP, % 71		I, %	CLVD, % 15	DBCP, % 85		I, %	CLVD, %	DBCP, % 100	
ΦA, ° 180	δA, ° 62	ΦB, ° 00	δB, ° 28	ΦA, ° 266	δA, ° 87	ΦB, ° 164	δB, ° 16	ΦA, ° 181	δA, ° 74	ΦB, ° 166	δB, ° 33
ΦP, ° 270	δP, ° 17	ΦT, ° 90	δT, ° 73	ΦP, ° 10	δP, ° 40	ΦT, ° 160	δT, ° 46	ΦP, ° 34	δP, ° 23	ΦT, ° 156	δT, ° 52
Q, % 48		ERR, Nm 0,34E+14		Q, % 55		ERR, Nm 0,29E+14		Q, % 59		ERR, Nm 0,36E+14	

Table 5. Source mechanism parameters of the 26th October 2007

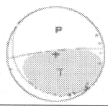
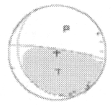
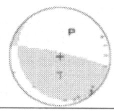
Date			Time			Energy, J			Coordinates, m (SG system)		
26.10.2007			3:01			$2\cdot10^7$			22498		11109
Full solution Reverse fault				Deviatoric solution Reverse fault				Double couple solution Reverse fault			
											
M_{ij}, Nm				M_{ij}, Nm				M_{ij}, Nm			
-0,34E+15	-0,19E+15	-0,13E+16		-0,79E+14	-0,99E+14	-0,44E+15		-0,16E+15	-0,15E+15	-0,64E+15	
-0,19E+15	-0,95E+14	0,21E+15		-0,99E+14	-0,59E+14	-0,38E+14		-0,15E+15	-0,59E+14	-0,12E+15	
-0,13E+16	0,21E+15	0,44E+15		-0,44E+15	-0,38E+14	0,24E+15		-0,64E+15	-0,12E+15	0,22E+15	
M_o· Nm 0,14E+16		M_T · Nm 0,14E+16		M_o· Nm 0,45E+15		M_T · Nm 0,47E+15		M_o· Nm 0,69E+15		M_T · Nm 0,69E+15	
I, % 0,2	CLVD, % 10,8	DBCP, % 89		I, %	CLVD, % 8	DBCP, % 92		I, %	CLVD, %	DBCP, % 100	
ΦA, ° 264	δA, ° 82	ΦB, ° 133	δB, ° 12	ΦA, ° 278	δA, ° 82	ΦB, ° 154	δB, ° 14	ΦA, ° 283	δA, ° 81	ΦB, ° 149	δB, ° 14
ΦP, ° 1	δP, ° 37	ΦT, ° 164	δT, ° 52	ΦP, ° 18	δP, ° 36	ΦT, ° 175	δT, ° 51	ΦP, ° 21	δP, ° 35	ΦT, ° 181	δT, ° 53
Q, % 48		ERR, Nm 0,59E+14		Q, % 53		ERR, Nm 0,35E+14		Q, % 60		ERR, Nm 0,46E+14	

Table 6. Source mechanism parameters of the 7th November 2007

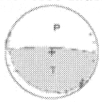
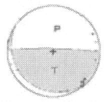
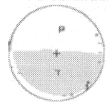
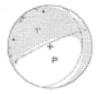
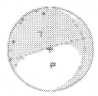
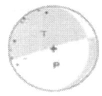
Date 07.11.2007			Time 10:07			Energy, J $5\cdot10^{8}$			Coordinates, m (SG system)		
									22508		11070
Full solution Reverse fault 				Deviatoric solution Reverse fault 				Double couple solution Reverse fault 			
M_{ij}, Nm				M_{ij}, Nm				M_{ij}, Nm			
-0,22E+16	-0,11E+16	-098E+16		-0,22E+16	-0,11E+16	-0,98E+16		-0,29E+16	-0,13E+16	-0,12E+17	
-0,11E+16	-0,38E+14	0,57E+14		-0,11E+16	-0,28E+14	-0,38E+14		-0,13E+16	-0,64E+14	-0,17E+15	
-0,98E+16	0,57E+14	0,45E+16		-0,98E+16	-0,38E+14	0,22E+16		-0,12E+17	-0,17E+15	0,30E+16	
M_o' Nm 0,11E+17		M_T ' Nm 0,12E+17		M_o' Nm 0,11E+17		M_T ' Nm 011E+17		M_o' Nm 0,13E+17		M_T ' Nm 0,13E+17	
I, % 7	CLVD, % 7	DBCP, % 86		I, %	CLVD, % 0,1	DBCP, % 99,9		I, %	CLVD, %	DBCP, % 100	
ΦA, ° 272	δA, ° 80	ΦB, ° 123	δB, ° 11	ΦA, ° 270	δA, ° 84	ΦB, ° 135	δB, ° 9	ΦA, ° 271	δA, ° 83	ΦB, ° 130	δB, ° 9
ΦP, ° 7	δP, ° 35	ΦT, ° 175	δT, ° 54	ΦP, ° 6	δP, ° 38	ΦT, ° 174	δT, ° 51	ΦP, ° 6	δP, ° 39	ΦT, ° 175	δT, ° 52
Q, % 45		ERR, Nm 0,34E+15		Q, % 52		ERR, Nm 0,27E+15		Q, % 60		ERR, Nm 0,36E+15	

Table 7. Source mechanism parameters of the 29th November 2007

Date 29.11.2007			Time 21:45			Energy, J $6\cdot10^{6}$			Coordinates, m (SG system)		
									22462		11121
Full solution Normal fault 				Deviatoric solution Normal fault 				Double couple solution Normal fault 			
M_{ij}, Nm				M_{ij}, Nm				M_{ij}, Nm			
-0,13E+15	-0,31E+15	0,19E+16		-0,14E+15	-0,32E+15	0,19E+16		-0,98E+13	-0,40E+15	0,17E+16	
-0,31E+15	0,47E+15	-0,63E+15		-0,32E+15	0,52E+15	-0,41E+15		-0,40E+15	0,24E+15	-0,48E+15	
0,19E+16	-0,63E+15	-0,11E+16		0,19E+16	-0,41E+15	-0,38E+15		0,17E+16	-0,48E+15	-0,23E+15	
M_o' Nm 0,22E+16		M_T ' Nm 0,25E+16		M_o' Nm 0,19E+16		M_T ' Nm 0,22E+16		M_o' Nm 0,19E+16		M_T ' Nm 0,19E+16	
I, % -8	CLVD, % -12	DBCP, % 80		I, %	CLVD, % -11	DBCP, % 89		I, %	CLVD, %	DBCP, % 100	
ΦA, ° 246	δA, ° 80	ΦB, ° 13	δB, ° 16	ΦA, ° 254	δA, ° 86	ΦB, ° 359	δB, ° 13	ΦA, ° 254	δA, ° 86	ΦB, ° 359	δB, ° 13
ΦP, ° 170	δP, ° 52	ΦT, ° 326	δT, ° 34	ΦP, ° 177	δP, ° 45	ΦT, ° 332	δT, ° 40	ΦP, ° 176	δP, ° 48	ΦT, ° 332	δT, ° 40
Q, % 40		ERR, Nm 0,11E+15		Q, % 47		ERR, Nm 0,11E+15		Q, % 55		ERR, Nm 0,12E+15	

The solution of the tremor mechanism for full tensor against the background of seam map sector presents the Figure 3. For the tremor of 12 September 2007 the direction of nodal plane azimuth can be correlated (within the limits of calculation error 20°) with the strike of the Knurów fault situated at the eastern side of the panel, and for the remaining tremors the direction of the modal plane azimuth is parallel to the strike of the fault zone which limits from the south the longwall 17 area. The exceptionally high share of the shearing component in the mechanism of focus testifies that in this area occur very high influence of stresses originating from tectonic structures. The type of reverse mechanism (displacement on the fracturing plane upwards) can indicate that in consequence of stress equalisation in the fault zone as a result of rock mass "relief" could arise fracturing of sandstone layers occurring at a high distance above the seam. On processes of this type can indicate the lack of equilibrium in the stress field distribution in a large area, because both in the north-western part of the "Knurów" colliery as well as on the eastern side at the "Budryk" colliery several seams were mined out. It should be also mentioned that the analysed tremors have not caused any effects and were not felt in underground workings. Thus the investigations carried out can indicate that the reason of occurred tremors was not only direct mining of the longwall 17, but there followed overlapping of mining-related stresses with residual stresses occurring in the fault zone.

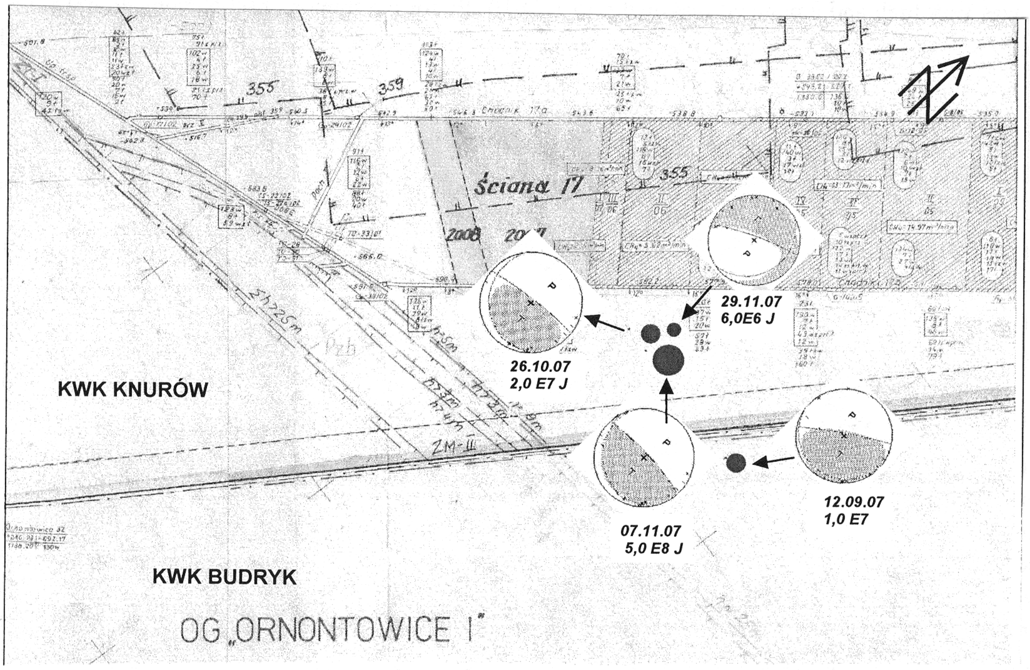


Figure 3. Position of tremor focus and their mechanism against the background of seam map sector

3.2. *Spectral parameters*

The spectral parameters of the source of analysed tremors were calculated from seismograms of the Seismological Network of the "Knurów" colliery. The results of source parameter calculations (averaged values from selected not re-controlled channels of the seismological network for the wave S presents Table 8.

Table 8. Source parameters

Date	Time	Energy, J	Source parameters					
			M_0, Nm	R_0, m	f_o, Hz	$\bar{D}$, m	$\Delta\sigma$, Pa
2007-09-12	14:45	1.0E+07	7.20E+11	73	6.8	1.38E-03	8.06E+05
2007-10-26.	23:45	2.0E+07	1.08E+12	72	7.5	2.16E-03	2.26E+06
2007-11- 07	10:07	5.0E+08	4.52E+13	104	5.8	4.24E-02	1.74E+07
2007-11- 29	21:45	6.0E+06	4.52E+11	82	4.2	2.35E-03	5.69E+06

The obtained values of source parameters for the analysed tremors indicate the regional character of these phenomena; their reason can be the trend to equalise tectonic residual stresses activated through conducted mining in the fault zone. The corner frequency is low and amounts on the average to 6 Hz. The seismic moment of analysed phenomena amounts from $4.52 \cdot 10^{11}$ Nm for the tremor of 29 November 2007 to $4.52 \cdot 10^{13}$ Nm for the tremor of 07 November 2007. By the largest focus radius equal to 102 m was characterised the tremor of 07 November 2007. The remaining tremors had radii equal to 73, 72 and 82 m. The displacement in the focus was from $1.38 \cdot 10^{-3}$ m for the tremor of 12 September 2007 to $4.24 \cdot 10^{-2}$ m for the tremor of 07 November 2007. The stress decrease, which means the difference between the stress in the focus before the tremor and stress after the tremor was very high and amounted maximally to $1.74 \cdot 10^{7}$ Pa for the tremor of 07 November 2007 and $2.26 \cdot 10^{6}$ Pa for the tremor of 26 October 2007, $8.05 \cdot 10^{5}$ Pa for the tremor of 12 September 2007 and $3.35 \cdot 10^{6}$ Pa for the tremor of 29 November 2007.

4 Mine tremor source mechanism induced by mining exploitation at the "Staszic" colliery

At the "Staszic" colliery on 23 February 2008 at 7.30 p.m. and 7.32 p.m. occurred two high-energy tremors, the first one with energy 8.0E+06 J ($M_L = 2.7$), and the second with energy 2.0E+07 J ($M_L = 2.9$), which led to the loss of functionality of workings in the area of longwall I (cross-cut Asea, transport incline). After tremor occurrence since 23 February 2008 extraction activities on longwall I was stopped on account of damages of workings. For these two tremors and remaining tremors with energy E ≥ 5.0E+03 J ($M_L \geq 1$) from the period 8 December 2007 – 29 March 2008 calculations of focal mechanism calculated using the seismic moment tensor inversion method. The specification of analysed tremors of shearing type of mechanism and explosive character presents Table 10.

From the analysed group of phenomena 23 tremors were characterised by the shearing type of focal mechanism. The fracturing process in the case of these tremors took place at the normal fault, and in their mechanism distinctly dominated the shearing component (from 60 to 75%). Figure 4 presents the position of analysed tremors and their focal mechanism for total solution of the seismic moment tensor of tremors with energy E ≥ 1.0E+05 J ($M_L = 2.7$) against the background of seam map sector. The direction of nodal planes and the corresponding with them fracture direction in the focus for high-energy tremors of 23 February 2008 with energy 8.0E+06 J ($M_L = 2.7$) and with energy 2.0E+07 J ($M_L = 2.9$), as well as of 25 February 2008 with energy 1.0E+05 J ($M_L = 1.7$) and of 29 March 2008 with energy 2.0E+05 J ($M_L = 1.8$) had the azimuth NE–SW or N–S. This direction, within the limits of the calculation error ± 20° was parallel to the course of the cross-cut Asea and transport incline and to the line of mined longwall front.

In the light of analysis carried out we can formulate the hypothesis that the reason of high-energy tremors causing the rockburst in the eastern panel could be exceeding of stresses in sandstone layers occurring above the seam 501, in the left zone of non-mined rock mass between the edges in seam 510, which are parallel to workings conducted in the seam 501. The direction of fracturing in focus of the remaining tremors with lower energies in the majority of cases had also the azimuth NE–SW as well as NW–SE and E–W.

For 12 phenomena one has obtained the type of focus of explosive character. The total tensor contained from 44 to 50% of explosive component, from 43 to 50% of the uniaxial tension component and from 0.5 to 17% of the shearing component. The high share of explosive and uniaxial tension components in the focal mechanism of this type indicates the domination of explosive processes in the seam as a result of overburden layer pressure.

Table 10. Specification of seismological parameters and parameters of focal mechanisms, which occurred during longwall I mining, in the seam 501/II over the period from 8 December 2007 to 29 March 2008 (NO- normal fault, RE – reverse fault)

Date	Time		Energy, J	Coordinates SG system, m		Tensor's components,%			Tape of focal mech.
	h	m		X	Y	I	CLVD	DBCP	
2007-12-10	4	52	1.0E+04	22522	-13776	-20	-20	60	NO
2007-12-12	23	25	2.0E+04	22528	-13777	-20	-20	60	NO
2007-12-17	12	20	6.0E+03	22428	-13717	-20	-20	60	NO
2007-12-23	8	36	8.0E+04	22421	-13822	-20	-20	60	NO
2007-12-29	22	17	7.0E+03	22432	-13767	-15	-15	70	NO
2008-01-24	9	29	4.0E+04	22379	-13719	-20	-20	60	NO
2008-02-13	11	49	3.0E+04	22485	-13790	-20	-20	60	NO
2008-02-16	15	13	6.0E+04	22407	-13661	-20	-20	60	NO
2008-02-19	9	59	2.0E+04	22428	-13569	-20	-20	60	NO
2008-02-21	10	39	2.0E+04	22424	-13658	-20	-20	60	NO
2008-02-22	7	8	8.0E+04	22383	-13679	-17	-20	63	NO
2008-02-22	16	36	2.0E+04	22414	-13717	-19	-20	61	NO
2008-02-23	16	21	2.0E+04	22433	-13702	-20	-20	60	NO
2008-02-23	19	30	8.0E+06	22457	-13631	-20	-19	61	NO
2008-02-23	19	32	2.0E+07	22322	-13622	-13	-17	70	NO
2008-02-23	19	42	2.0E+04	22474	-13668	-19	-20	61	NO
2008-02-23	20	15	1.0E+04	22430	-13614	-11	-14	75	NO
2008-02-23	21	0	2.0E+05	22358	-13858	-19	-19	62	NO
2008-02-24	14	44	2.0E+04	22465	-13621	-20	-20	60	NO
2008-02-25	1	37	2.0E+05	22306	-13638	-12	-18	70	NO
2008-02-25	10	10	1.0E+05	22389	-13692	-20	-20	60	NO
2008-03-25	14	6	3.0E+05	22286	-13640	-11	-14	75	NO
2008-03-29	5	18	3.0E+05	22295	-13643	-18	-20	62	NO
2007-12-08	2	5	7.0E+03	22599	-13833	46	47	7	RE
2007-12-19	23	24	5.0E+03	22458	-13776	50	49	1	RE
2007-12-22	17	7	8.0E+03	22547	-13822	49	48	3	RE
2008-01-06	6	40	6.0E+03	22503	-13748	49	49	2	RE
2008-01-12	23	1	6.0E+03	22394	-13708	50	49	1	RE
2008-02-13	6	5	5.0E+03	22324	-13589	44	43	13	RE
2008-02-13	6	7	5.0E+03	22334	-13591	49	49	2	RE
2008-02-13	22	8	9.0E+03	22460	-13821	43	40	17	RE
2008-02-20	21	12	5.0E+03	22454	-13638	49	49	2	RE
2008-02-22	14	31	5.0E+03	22410	-13670	50	49	1	RE
2008-02-23	6	58	8.0E+03	22417	-13659	49	49	2	RE

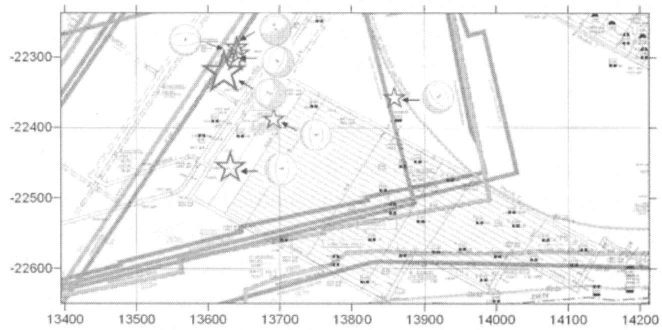


Figure 4. Focal mechanism of tremors with energy E ≥ 1.0E+05 J (M_L = 1.7) against the background of seam 501/II map sector

5 Summary

The results of investigations of tremor focus mechanism and source parameters carried out in different regions of the Upper Silesian Coal Basin allow to obtain information about destruction processes of rock mass disturbed by conducted mining exploitation. A distinct variability of mechanisms of focus of registered tremors according to the region's tectonic features, location of the tremor focus towards the longwall front and existing extraction events was stated.

Two types of seismicity were separated, the so-called mining and mining-tectonic seismicity. The first type of phenomena is directly connected with the conducted mining activity and occurs in the neighbourhood of active mine workings. There are phenomena weaker with respect to energy and are characterised in the majority by the explosive type of the of mechanism.

The second type of mining-tectonic seismicity originates as a result of connection of mining-related and residual stresses occurring in deep structures of the Upper Silesian Coal Basin.

These are high-energy tremors, occurring in regions of tectonic zones, frequently felt by the population on the surface. The most often type of mechanism of focus of these tremors is the normal slide mechanism with the appearing horizontal displacement in the tremor focus. The azimuth of disruption planes and their dips for these phenomena correlate with the strike and dip of faults, in the vicinity of which the focus of tremors are located.

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