VERSITA

Arch. Min. Sci., Vol. 57 (2012), No 4, p. 871–886

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.2478/v10267-012-0057-7

KRYSTYNA STEC*

FOCAL MECHANISMS OF MINE-INDUCED SEISMIC EVENTS AN EXPLANATION OF GEOMECHANICAL PROCESSES IN THE AREA OF LONGWALL 6, SEAM 510 IN HARD COAL MINE "BOBREK-CENTRUM"

MECHANIZM OGNISK INDUKOWANYCH WSTRZĄSÓW GÓRNICZYCH WYJAŚNIENIEM PROCESÓW GEOMECHANICZNYCH W REJONIE ŚCIANY 6, POKŁAD 510 W KOPALNI „BOBREK-CENTRUM"

Exploitation in a coal mine "Bobrek-Centrum" of the longwall 6 in seam 510 has led to the occurrence of very high seismic activity. From January 2011 to June 2012 took place almost 3500 tremors with the energy of 10^2-10^4 J and 95 tremors of energy more than to 10^5 J. In an attempt to identify the character of that seismicity, calculations of focal mechanism parameters were carried out, and according to them local stress field was determined. Three periods of exploitation of longwall 6 were distinguished which vary in type of focal mechanism. Tremors, which occurred in exploitation periods I and III were characterized by normal slip mechanism, occurred due to domination of vertical principal stresses σ_1, horizontal intermediate stresses σ_2 and minimal ones σ_3. Such stress arrangement characterizes local state of rock mass behaviour as a result of cracking and collapse of sandstone, tremor-generating strata during advancing exploitation. In exploitation period II, of non-shearing mechanism of foci occurred. That was the period of change of longwall run from the NE-SW direction to E-W direction, that is the period of so called "slanting" of exploitation front. It can be presumed that this type of tremor mechanism could have occurred due to a sudden coal bed load by superimposed roof strata, which may have led to extreme load conditions and to a dynamic disintegration of seam part. It was confirmed by geomechanical calculations, which indicated that in the region of rockburst existence on 19.07.2011, layers which were located above and under seam 510 in area of longwall no. 6 were strongly deformed locally causing compression of certain parts of seam.

Keywords: seismic event, rockburst, focal mechanism, local principal stress

Eksploatacja w kopalni „Bobrek-Centrum" ściany 6 w pokładzie 510 powodowała występowanie bardzo wysokiej aktywności sejsmicznej. W okresie styczeń 2011-czerwiec 2012 wystąpiło prawie 3500 wstrząsów o energii 10^2-10^4 J oraz 95 wstrząsów o energii 10^5-10^6 J. W celu poznania charakteru tej sejsmiczności przeprowadzono obliczenia parametrów mechanizmu ognisk, na podstawie których określono

* CENTRAL MINING INSTITUTE, PL. GWARKÓW 1, 40-166 KATOWICE, POLAND

lokalne pole naprężeń. Wyróżniono trzy okresy eksploatacji ściany 6 różniące się typem mechanizmu ognisk. Wstrząsy, które wystąpiły w I i III okresie eksploatacji charakteryzowały się mechanizmem poślizgowym normalnym, występowały w wyniku dominacji pionowych naprężeń głównych σ_1 oraz poziomych naprężeń pośrednich σ_2 i minimalnych σ_3. Taki układ naprężeń charakteryzuje lokalny stan zachowania górotworu powstający w wyniku pękaniu i załamywaniu się piaskowcowych warstw wstrząsogennych w czasie postępującej eksploatacji. W II okresie eksploatacji występowały wstrząsy o nieścinającym mechaniżmie ognisk. Był to okres zmiany biegu ściany z kierunku NE-SW na kierunek E-W czyli okres tzw. „skosowania” frontu eksploatacyjnego. Można przypuszczać, że tego typu mechanizm wstrząsów mógł wystąpić w wyniku nagłego obciążenia pokładu przez nadległe warstwy stropowe co mogło doprowadzić dla skrajnych warunków obciążenia i do dynamicznego rozpadu fragmentu pokładu. Potwierdziły to obliczenia geomechaniczne, które wykazały, że w rejonie zaistnienia tąpnięcia w dniu 19.07.2011 r. warstwy położone nad i pod pokładem 510 w rejonie ściany 6 były lokalnie bardzo silnie odkształcone powodując ściskanie określonych fragmentów górotworu.

Słowa kluczowe: wstrząs górotworu, mechanizm ogniska, lokalne naprężenia główne

1. Introduction

A consequence of mining in many mines of the Upper Silesian Coal Basin is high seismic activity posing a risk of rockbursts. This threat results from geological and mining conditions in a particular exploitation field. The essential significance for the level of seismic activity have strength parameters of coal and surrounding rocks as well as stress distribution in the area of conducted mining excavations. Stress state in a given exploitation field is a result of interaction of lithostatic, tectonic and so called "exploitation" stresses connected with the performed exploitation. Local field of principal stresses, determined mainly by 'exploitation' stresses can be recreated from seismological data analysis – parameters of focal mechanism. As it can be inferred from the undertaken research, formation of tremors of various mechanism of foci is dependent on the spatial position of principal stresses (Michael, 1987; Zoback, 1992; Arnold & Townend, 2007). Calculations of local stress field in the region of longwall 6 extracted in seam 510 in "Bobrek-Centrum" mine were conducted on the basis of results of focal mechanism with the use of My Fault programme (Panagaea Scientific, 2007). It is a method used for many years to determine stress distribution for earthquakes (Angelier, 2002; Pasquale et al., 2008; Vicente 2008; Fotikowa et al., 2010; Katsumata et al., 2010), which because of the same causes of occurrence of earthquakes and mine-induced tremors was used for mining seismicity. The main objective of the presented results is to demonstrate a new method of evaluation of stress field in the regions with high seismic activity based on parameters of focal mechanism. It is the next stage in explaning with destruction processes taking place in rock mass affected by mining exploitation. Adopting this type of research substantiated high-energy seismic phenomena occurring in the region of the longwall 6, one of which of 19.07.2011 caused a direct threat to the exploitation works displayed by the damage in longwall 6 at a length of 42 m and a threat to human life.

It is assumed that the obtained research results will contribute to a better assessment of rockburst danger and in consequence they will allow the application of effective preventive actions with a view to reduce the seismic impact on the mine workings.

2. Characteristics of study area

The investigations encompassed the area of longwall 6 located in the bottom layers of seam 510 in the eastern part of mining area of "Bobrek-Centrum" hard coal mine, in the pillar of Bytom city. A map with the contour of mine workings and edges of seams is presented in Fig. 1a. The depth of deposition of seam 510 is variable and amounts to 730 m in the area of cross-cut of longwall 6, and then decreases to about 560 m in the area of the line of its run termination. Seam inclination is 6÷12° in the south-west direction, and its thickness changes within the limits from 9.0 to 9.6 m. Geological construction of rock mass, both above and below seam 510 is characterized by its high variability in lithology (Fig. 1b). Above the seam 510 there is alternation of sandstone, argillaceous schist and sandy shale strata and partially extracted seams 507, 506, 504 and 503. Between seams 507 and 504 do not exist tremor-generating homogeneous layers of high thickness. Such strata occur within the distance of about 70 m over seam 510. It is composed of a compact, homogeneous rock package (sandy shale and sandstone) with total thickness of 76 m, over which there are deposited partially extracted seams 501, 419 and 418, away from the roof of seam 510 of about 124 m, 128 m and 132 m respectively.

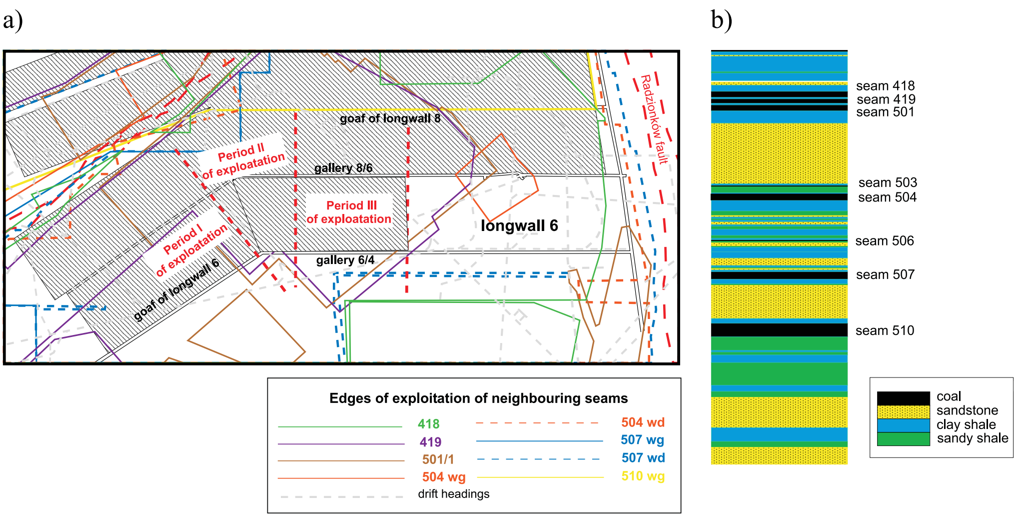


Fig. 1. Geologic and mining situation in the area of longwall 6, seam 510, Bobrek-Centrum hard coal mine

The variability of geological structure of rock mass is noticeable also in roof floor layers of seam 510. There are alternate layers of argillaceous schist and sandy shale and below 30 m there is a layer of sandstone and subsequently to the depth there are sandy shale and argillaceous schists.

The longwall 6 was started on 21.01.2011. Exploitation was run with transverse and diagonal backfilling system (hydraulic filling), to a height of 2.4 m, along goaf fillings of terminated from the north longwall 8. Exploitation with backfilling forced by the need to protect the downtown of the city Bytom. Owing to geological and mining diversity there can be distinguished three periods of exploitation of longwall 6 shown in fig. 1a.

The analysis of seismic activity in the area of longwall 6 was carried out in correlation with the three periods of exploitation. Generally, the level of seismic activity was very high (Table 1 and Fig. 2). In the first period (I) there were registered more than 1500 low-energy tremors with energies of 10^2-10^4 J. During movement of longwall 6, under parallel to its front, edges sections of seams 419 and 501, there were recorded increased activity manifested by the occurrence of 14 tremors with an energy of 10^5-10^6 J. The epicentres of these tremors were present both, in front and behind its front, but the majority occurred at the beginning of the front. In the second half of May 2011, a larger number of tremors was recorded in the area of existence of parallel to the longwall front, edges of seams 419 and 501.

TABLE 1

Summary of seismic tremors registered during run of longwall 6 in the period January 2011-June 2012

Extraction period	Number of tremors in particular energetic classes					Number of tremors in total	Amount of energy, J
	10^2 J	10^3 J	10^4 J	10^5 J	10^6 J		
21 January 2011 - mid-June 2011	675	692	148	13	1	1529	$1{,}33 \cdot 10^7$
mid-June 2011 - 11 November 2011	187	295	125	22	8	638	$4{,}19 \cdot 10^7$
12 November 2011 - 30 June 2012	408	593	365	44	7	1417	$5{,}1 \cdot 10^7$

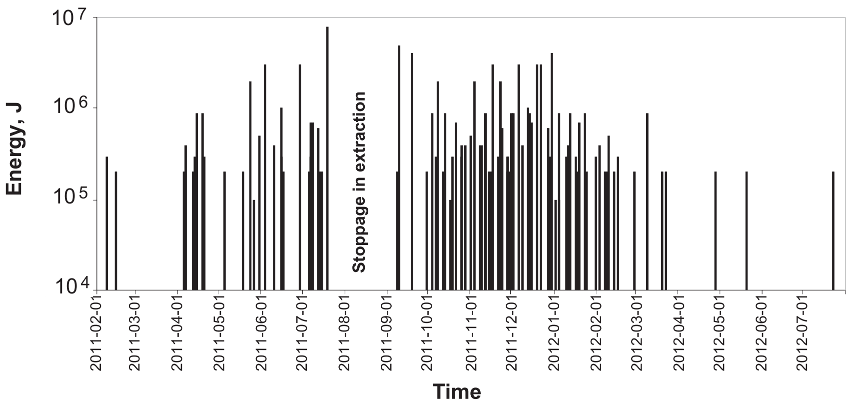


Fig. 2. Histogram of tremors of energy $E \geq 10^5$ J in the period of extraction of longwall 6 (January 2011-June 2012)

In the second period (II), lasting from mid-June to mid-November occurred the so called front "slanting" – front of the longwall was located diagonally to roadways. During that period, there was a decrease in the number of low-energy tremors 10^2-10^4 J observed (about 600 earthquakes), and an increase of the number of higher energy tremors observed (22 tremors of energy of 10^5 J, 8 tremors with an energy of 10^6 J). Tremors of higher energy were located in close proximity to the front of the longwall 6 and heading 8/6 (northern part of longwall 6). Recorded tremors did not affect excavations, with the exception of local loosening of coal side wall – tremor of 03.06.2011 with the energy $3.0 \cdot 10^6$ J, and the tremor from 19.07.2011 with the energy of $8.0 \cdot 10^6$ J, which caused the rockburst. There was damage of the longwall at a length of 42 m (the roof was damaged, there was an upheaval of floor, which caused the damage to the longwall conveyor, the construction of the filling dam was also damaged). In addition, three people have been injured. Following a rockburst there was a stoppage in exploitation until 19.11.2011.

In the third period (III), extending from mid-November 2011 till the end of June 2012 (end of the analysis) longwall 6 was extracted in parallel to the goaf of longwall 8 towards the E-W direction. In the initial phase of this period (until the beginning of March 2012) there was a considerable number of tremors, both low- and high- energy. There were 672 in total, including 40 tremors with an energy of 10^5 J and seven with an energy of 10^6 J. In the next period to the end of the analysis took place mainly low-energy phenomena from 10^2-10^4 J (694 tremors) and only 4 tremors of energy of 10^5 J.

3. Results of geomechanical analysis

A major issue in the conducting mining operations is the problem of deformation of undermined roof layers. Exploitation of deposits affects the original state of stress in the rock mass in the area of workings. Above the edge of already created or being formed goaf, particular layers forming the direct and basic roof are subject to deformations in the direction of cavern. Owing to the layer structure of rock mass, forming it subsequent layers will behave as a system of fastened in it plates, deformed under the influence of the load of overlay. A consequence of the above is their divisibility primary along the planes of weakened cohesion of bedding direction, which is accompanied by seismic phenomena of energy being the function of among others the intensity of carried out exploitation (Drzewiecki, 2004). Exceeding critical curvatures of bending of layers above formed edges will result in their dynamic division with a direction transverse to bedding (Makówka, 2009; Marcak 2012). In order to assess the state of rock mass deformation in the area of the longwall 6 at the time of rockburst occurrence on 19.07.2011, the analytical calculation of vertical displacement and the curvature of the deformation of rock layers separated was made. Calculations were performed for the two extracted horizons located 10 m below deposit 510 (horizon I) and 20 m above the deposit 507 (horizon II), respectively. The calculation results obtained for the horizon I allow to assess the impact of exploitation of seam 620, deposited at a distance of about 220 m below, on the state of deformation of the floor of the direct seam 510. Calculations made for the horizon II allow to assess the state of deformation of the roof layers affected by exploitation of seams 620, 510 and 507.

Calculations for the horizon I showed that the values of vertical displacement of the floor layer of seam 510 in the longwall 6, amounted from 0.1 m in the area of the heading 8/6 to about 0.05 m in the middle of the longwall 6 panel. In the area of heading 6/4, vertical displacement values were less than 0.05 m. For the second calculation horizon (II), in the area above the longwall 6 panel, vertical displacement values are within the limits from 0.65 m to 2 m. State of deformation of the rock mass at the assumed horizon is shown in Fig. 3. For greater clarity, the Fig. 3 has been increased in the Z axis (vertical). We can see clearly the presence of omnidirectional deflection of the horizon surface, which should be identified with the deflection of the layers in its environment. Such character of deformation was initiated in the region of the epicentre of the tremor of 07.19.2011, located 30 m behind the front of longwall 6. The process

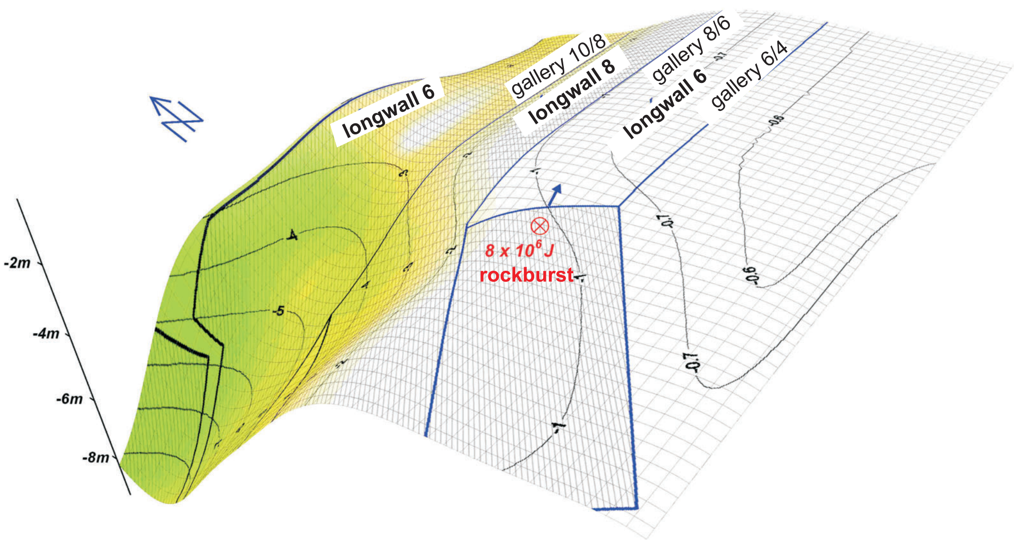


Fig. 3. Spatial visualization of the distribution of the value of vertical displacement layer deposited in the roof of seam 510 (horizon II – 20 m above seam 507)

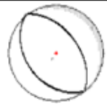
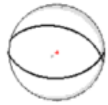
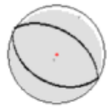
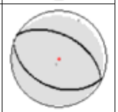
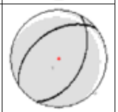
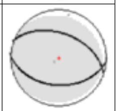
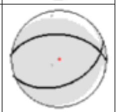
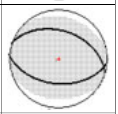
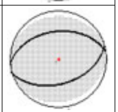
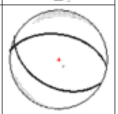
of deformation occurred towards the north, to the crossing of longwall front with heading 8/6, and the directions of the north-east and north-west. Basins with varying shape and slopes were developed in those regions.

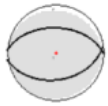
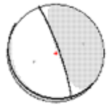
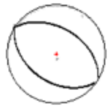
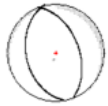
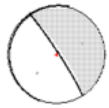
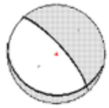
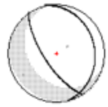
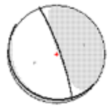
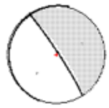
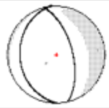
4. Results of the analysis of the focal mechanism

Analysis of the focal mechanism of seismic events using the method of seismic moment tensor inversion gives information about the processes of fracturing taking place in tremors foci. Theoretical foundations of the method are widely referred to in literature and were the subject of many publications (Aki & Richards, 1980; Gibowicz, 1994; Stec, 2007, 2009). Calculation of the focal mechanism of high-energy tremors of energy $E \geq 10^5$ J connected with extraction of longwall 6 in seam 510 in hard coal mine Bobrek-Centrum has been made with the software FOCI (Kwiatek, 2009) on the basis of seismograms registered by the mine seismologic network. The seismologic network in the period of investigations was compose of 20 stations evenly surrounding the region of longwall, which was the fundamental principle for proper determination of coordinates of tremors foci as well as their mechanisms. Computations were made with in time domain using the first motion amplitudes and signs P wave. An example of the results of calculations the parameters of focal mechanism is presented in Table 2. while their location and focal mechanism is presented in Fig. 4.

TABLE 2

An example of the results of calculations the parameters of focal mechanism of high-energy tremors occurring during exploitation of longwall 6/510 in hard coal mine Bobrek-Centrum (denotations*)

Date y-m-d	Time h:m:s			Energy J	Nodal planes		Axes of stress		Tensor com-ponents, %			Region/Group Type of mechanism	
					A Φ°/δ° λ°	B Φ°/δ° λ°	P Φ°/δ°	T Φ°/δ°	ISO	CLVD	DC		
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
2011-04-06	5	9	57	$4 \cdot 10^5$	323/51 -90	143/39 -90	233/84	53/6	-20	-20	60	NO/A	
2011-04-14	11	57	10	$9 \cdot 10^5$	282/46 -81	90/44 -99	267/84	6/1	-19	-20	61	NO/A	
2011-04-18	9	11	24	$9 \cdot 10^5$	160/46 -81	328/44 -99	144/84	244/1	-20	-18	62	NO/A	
2011-05-23	18	19	4	$2 \cdot 10^6$			30/5	224/85	48	50	2	EXP/C	
2011-06-03	19	49	33	$3 \cdot 10^6$			25/5	226/85	48	50	2	EXP/C	
2011-06-16	12	17	28	$1 \cdot 10^6$			130/1	223/77	48	49	3	EXP/C	
2011-06-29	17	56	53	$3 \cdot 10^6$			12/3	259/83	47	47	6	EXP/C	
rockburst 2011-07-19	**18**	**6**	**39**	$\mathbf{8 \cdot 10^6}$			**351/3**	**247/78**	**47**	**46**	**7**	**EXP/C**	
2011-09-09	18	8	3	$5 \cdot 10^6$			104/55	29/35	48	49	3	EXP/C	
2011-09-19	17	47	8	$4 \cdot 10^6$			74/47	262/44	46	46	8	EXP/C	
2011-11-11	8	8	55	$9 \cdot 10^5$	278/49 76	118/43 105	124/79	287/10	20	19	60	NO/B	

1	2	3	4	5	6	7	8	9	10	11	12	13	14
2011-11-17	4	17	8	$3 \cdot 10^6$			358/3	235/85	47	48	5	EXP/C	
2011-11-22	12	19	2	$2 \cdot 10^6$	340/82 -85	127/9 -123	256/52	66/37	18	18	64	NO/B	
2011-12-06	19	22	50	$3 \cdot 10^6$	299/47 -94	125/43 -86	152/87	32/2	-20	-20	60	NO/B	
2011-12-12	3	0	41	$1 \cdot 10^6$	338/59 -96	168/41 -83	205/83	73/4	-20	-20	60	NO/B	
2011-12-19	12	31	56	$3 \cdot 10^6$	326/85 -96	197/8 -40	230/49	62/40	-19	-18	63	NO	
2011-12-22	9	54	57	$3 \cdot 10^6$	318/76 -80	102/18 -124	242/58	40/30	18	20	62	NO	
2011-12-30	11	26	33	$4 \cdot 10^6$	145/70 -83	346/20 -108	46/64	243/25	-16	-19	65	NO/B	
2012-01-05	14	43	45	$9 \cdot 10^5$	338/82 -85	125/9 -123	256/62	66/37	18	18	64	NO/B	
2012-01-13	16	50	51	$9 \cdot 10^5$	331/47 -93	156/44 -86	185/87	64/2	-20	-20	60	NO	
2012-01-23	4	31	21	$9 \cdot 10^5$	326/85 -96	199/8 -42	230/49	62/40	-18	-18	64	NO/B	
2012-02-10	22	54	22	$5 \cdot 10^5$	338/50 -96	168/41 -83	205/83	73/4	-20	-20	60	NO/B	
2012-03-09	6	17	52	$9 \cdot 10^5$	345/62 -96	177/29 -80	242/73	80/16	-20	-18	62	NO/B	

* Denotations: ΦA,B – nodal plane azimuth A,B; δA,B – dip of plane A,B; λ – slip angle; ΦP,T – axis azimuth P,T; δP,T – plunge of axis P,T; ISO – percentage of isotropic component; CLVD – percentage of compensated linear vector dipole component, compression /-/ or tension /+/; DC – percentage of shear component (double-couple); NO – normal fault; RE – reverse fault; EXP – non-shear mechanism.

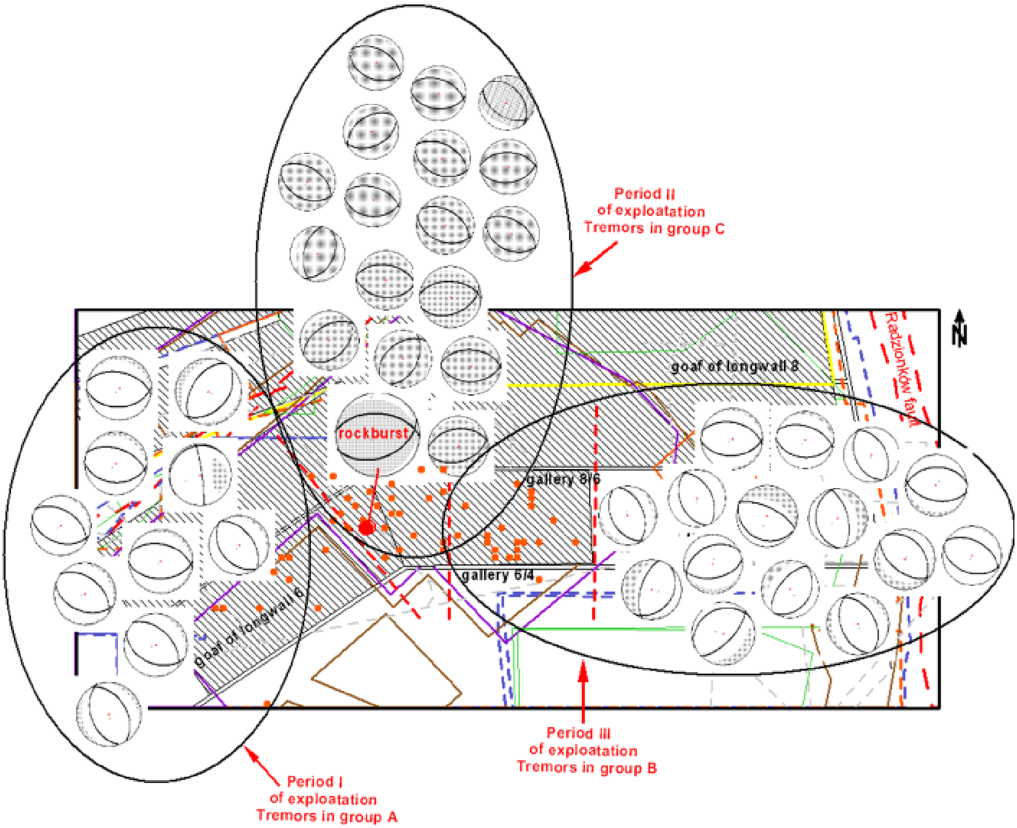


Fig. 4. Location and focal mechanism of high-energy tremors from longwall 6 seam 510 in hard coal mine Bobrek-Centrum

Three groups of tremors (group A, B and C) of various mechanisms have been selected. Tremors in a given group characterized with very similar parameters of received solutions of focal mechanisms. Tremors in group A in I period of extraction of longwall 6 lasting until the end of May 2011 and were characterized with normal slip mechanism. Full tensor included about 20% explosions, about 20% component of uniaxial tension and about 60% shear component. Compressive stresses P were of direction approximate to vertical while tensile stresses T were horizontal. For a few tremors strike azimuth of one of the nodal planes was within the limits of compute error (±20°) parallel to the line of exploitation front.

Tremors, which have been distinguished in group B characterized with normal slip mechanism. Full tensor included similarly to the group of tremors A about 20% of explosions, about 20% component of uniaxial tension and over 60% shear component. Compressive stresses P were of direction approximate to vertical and tensile stresses T were horizontal. For the majority of tremors strike azimuth of one of the nodal planes within the compute error (±20°) was possible to correlate with strike of front or goaf of longwall 8 course. These tremors occurred as a result of fracturing and fall of overlaying roof strata. In both groups the type of foci mechanism and the direction of cracking in a focus, indicated that seismic activity reflected typical destruction processes of rock mass taking place as a result of fracturing of roof strata with the longwall advance.

In group C, foci of high-energy tremors were characterized with non-shear mechanism. Tremors with this type of mechanism took place in II period of extraction of longwall 6. Full tensor included from 45% to 50% of explosions, the same contribution of component of uniaxial tension as well as very small contribution of shear component (up to 10%). Exceptionally large explosive components and uniaxial tension in the mechanism of this type of foci may indicate the domination of destructive processes taking place in seam or in its direct vicinity. The tremor which caused rockburst on 19.07.2011 belonged to his type of tremors.

4. Results of calculations of local tensor of stresses

A method of determination of a local stress field on the basis of focal mechanism of earthquakes has been utilized for many years in determination of stress field in the regions of earthquakes (Angelier, 2002; Pasquale et al., 2008; de Vicente, 2008; Fotikowa et al., 2010; Katsumata et al., 2010). Owing to the probability of occurrence of earthquakes and mining tremors, a method of determination of average local stress fields was adopted for mining seismicity. Physical foundations of the method have been presented in a publication (Dubiński & Stec, 2001; Stec, 2012). On the basis of parameters of focal mechanisms, in particular cases with domination of shear processes in foci it was possible to determine the location of failure plane as well as direction of displacement on this plane. Then, on the basis of these parameters the relative local stress field is determined. Types of foci mechanisms and system of principal stresses (σ_1, σ_2, σ_3) corresponding to them presents Fig. 5.

The fundamental assumption of the method provided by McKenzie (1969) is assumption that cracking process in the focus develops along a specific plane and slip vector is parallel to shear stress situated in this plane. Due to the fact that in a solution of focal mechanism two potential cracking planes in focus are obtained, then indication of one of them as proper failure plane was based on Coulomb-Mohr strength criterion. The criterion determining the conditions of occurrence of fracturing in the rock mass assumes that rock destruction takes place as a result of shear taking place in the plane, in which shear stress bursts on the plane, τ, counterbalances normal stress, σ, and forces of internal friction (Reches, 1987; Angelier, 2002; Townend, 2006). This criterion was adopted in the programme MyFault (Pangaea Scientific, 2007). As a result of calculations, the following parameters are obtained:

- azimuth and plunge of principal stresses σ_1, σ_2, σ_3,
- parametr $R = (\sigma_2 - \sigma_3)/\ \sigma_1 - \sigma_3)$; assuming that there is $\sigma_1 \geq \sigma_2 \geq \sigma_3$, parameter R assumes values $0 \leq R \leq 1$,
- diagram for the state of stresses in coordinate system σ, τ with the assumption that the maximum stress $\sigma_1 = 1$ and $\sigma_3 = 0$ (Mohr's circle),
- azimuth of shear stress (rose of cracks).

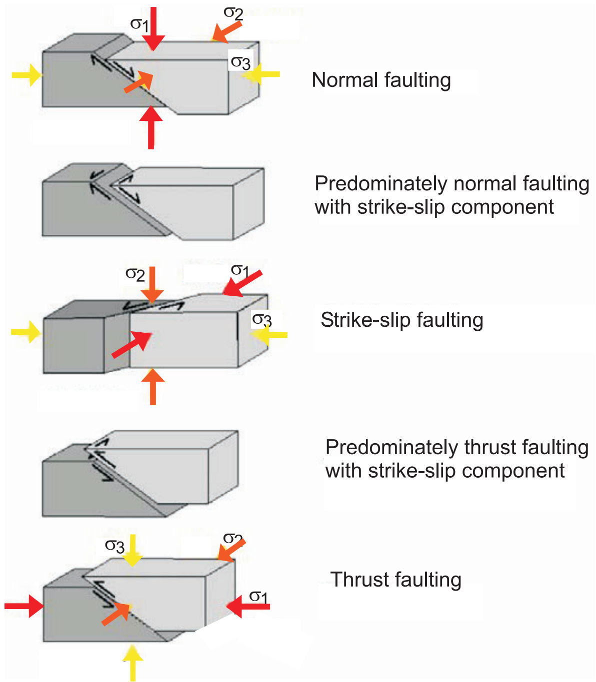


Fig. 5. Types of foci mechanisms and a system of principal stresses (σ_1, σ_2, σ_3)

The dependence between axes of stresses σ_1, σ_2, σ_3 and a direction of slip determine the following parameters:

- angle between the direction of slip and maximum shear stress calculated on face of fault (Misfit angle),
- angle between cracking plane and maximum principal stress σ_1 (Fault angle),
- angle between the maximum stress σ_1 and a normal to cracking plane, in which slip occurs – friction angle (Friction angle); coefficient of friction is equal to tg (Φ),
- average shear stress (Shear Stress),
- direction of shortening – extension, thid direction is the main direction of strain state (tension) of strain in a given region (Shortening/Extension),
- horizontal stress – direction of stress is located in horizonatal plane.

On the basis of analysis results of tremor foci from the area of longwall 6 calculated the above specified parameters, on the basis of which stress state of the rock mass was determined in the region of conducted extraction. Calculations of stress field were carried out for selected two groups of tremors A and B, which took place in I and III period of extraction of longwall 6. The findings are presented in Table 3.

TABLE 3

Parameters of stress field in the area of longwall 3, seam 501 in hard coal mine Bobrek-Centrum

Parameter	Group of tremors A	Group of tremors B
principal stress σ_1, (azimuth/plunge)	300°/80°	166°/85°
principal stress σ_2, (azimuth/plunge)	96°/9°	45°/3°
principal stress σ_3, (azimuth/plunge)	187°/4°	315°/4°
parameter $R = (\sigma_2 - \sigma_3)/\sigma_1 - \sigma_3)$, $\sigma_1 \geq \sigma_2 \geq \sigma_3$	0.08	0.09
Misfit Angle ± error	5.3° ± 4.4°	6.2° ± 5.7°
Fault Angle ± error	31.5° ± 7.2°	34.3° ± 13.1°
Friction angle	29.5°	36.7°
ralative Shear Stress	0.405 ± 0.006	0.400 ± 0.01
direction of shortening – extension (azimuth/plunge)	345°/84°	164°/86°

In the I period of longwall extraction lasting from January 2011 to May 2012 occurred tremors with foci of normal slip type (group A). The calculated distribution of stresses was as follows (Fig. 6): principal stress σ_1 affected in vertical direction (azimuth – 300°, plunge – 80°) and intermediate principal stress σ_2 (azimuth – 96°, plunge – 9°) and minimum σ_3 (azimuth – 187°, plunge – 4°) were horizontal. Coefficient R was equal to 0.08. Relative maximum shear stress (Shear Stress) amounted to 0.4 and its azimuth presented in Fig. 7 was of a direction parallel to

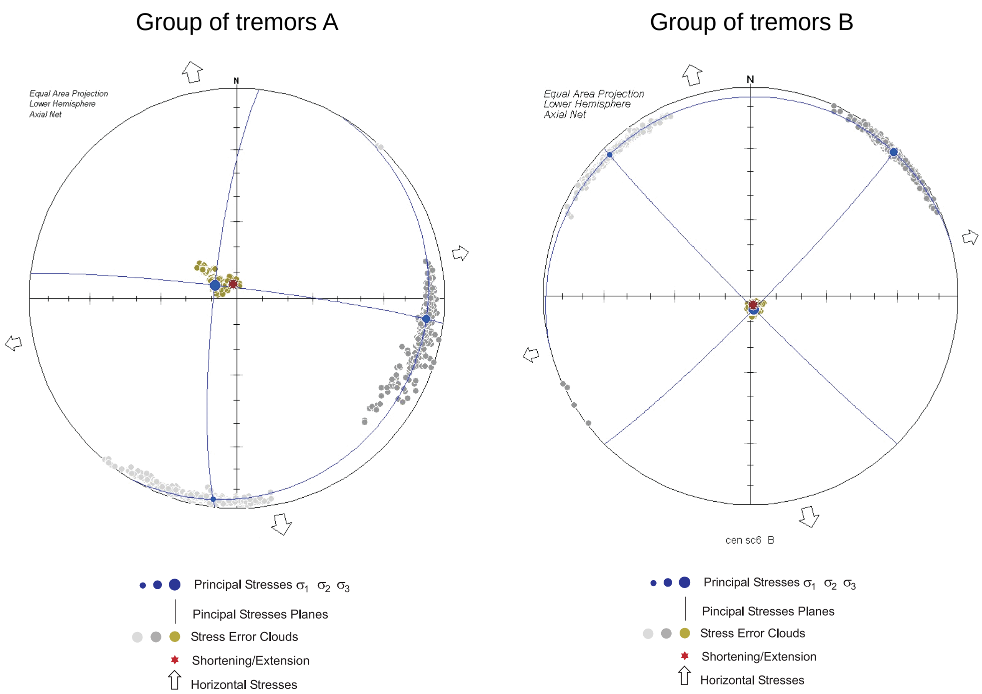


Fig. 6. Results of calculations of parameters of stress field for tremors of slip focal mechanism from the area of longwall 6

front strike. Friction coefficient was equal to 0.57 (Φ = 30°). Horizontal stress marked in Fig. 6 and 7 by white arrows is tensile stress and its dominant direction NNW-SSE. Shortening – extension axis (Shortening/Extension), which is direction of strain state (tension) in a given region was directed vertically along the line of the front (azimuth – 345° and plunge – 84°). This type state of stresses with dominance of principal stress σ_1 directed vertically, corresponds to typical

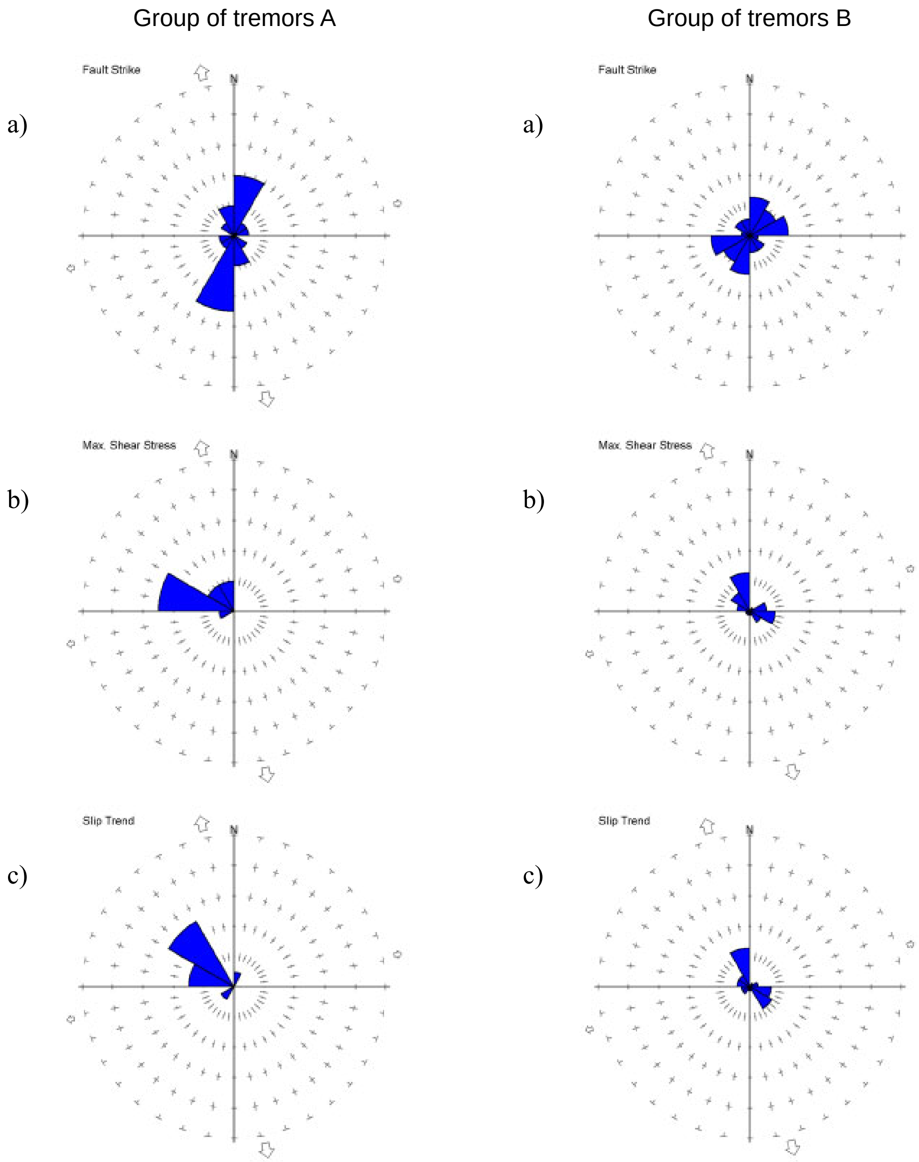


Fig. 7. Strike azimuth of cracking plane (a), direction of shear stress (b) as well as direction of slip (c) for high-energy tremors from longwall 6

conditioncs reflecting the influence of overlaying strata yielding to cracking and falling in the course of advancing exploitation.

This method also allows to present relative state of stresses on the basis of Mohr circle in coordinate system of normal stress σ and shear stress τ. With the detemined system of stresses σ_1, σ_2, σ_3 a certain critical state is obtained and destruction of rock structure occurs as a result of brittle fracture. Fig. 8 for the analysed groups A and B of tremors illustrates an equivalent of Mohr's circles computed with the assumption that that stress $\sigma_1 = 1$ and $\sigma_3 = 0$. As it is seen, for the majority of tremors (black dots) state of stress in the area of foci indicates that the value of normal stress σ is lower than shear stress τ. Such state designates a medium characterized with higher shear strength, in which tremors are characterized with stronger dynamic impact, which constitutes more serious threat for the carried out exploitation.

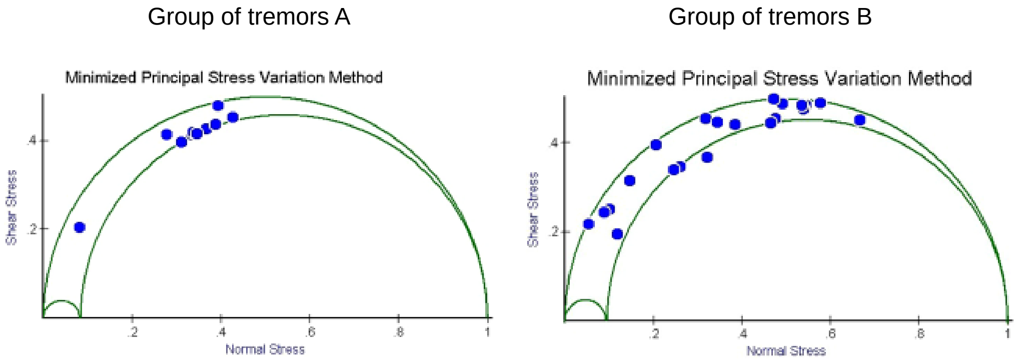


Fig. 8. Triaxial state of stress in the area of high-energy tremors from longwall 6 in coordinate system σ, τ

Subsequently, for the group of tremors C, which occurred mainly in II period of extraction of longwall 6 lasting from the end of June to the middle of November, distribution of stresses was not determined. In that period took place a change of location of longwall front (so called "slanting") tremors characterized with high content of non-shear component there were no grounds for separating planes of cracking in foci (Table 2).

6. Summary

The performed geomechanical analysis with reference to the parameters of focal mechanism of seismic tremors as well as distribution of stress field resulting from it allowed to define the most probable reasons of high seismic activity and the occurred rockburst. On the basis of carried out calculations a thesis can be advanced that tremor mechanism are helpful for determination of the way of rock mass destruction.

Three periods of longwall 6 extraction differing in the type of focal mechanism have been distinguished. Tremors which occurred in the I and III period of exploitation were characterized by normal slip mechanism. Azimuth of extent of cracking plane in the I period of extraction was approximate to N-S and in III period to W-E. Tremors with his type of foci took place as a result of domination of vertical principal stresses σ_1 as well as intermediate horizontal stresses σ_2 and minimum σ_3. In the both periods, shear stresses acted in a direction similar to front extent. Shortening – extension axis, wich is a direction of the highest strain state (tension) in a given region was directed vertically and its a azimuth could be related to the front line. Horizontal stress was tensile stress of NNW-SSE direction.

Such a system of stresses characterizes a local state of rock mass behaviour as a consequence of fracturing and falling of bump-generating sandstone strata in the time of advancing exploitation which was a consequence of unmined coal and goaf arrangement in a given area.

A hypothesis may be accepted that this type of seismic activity despite the occurrence of high-energy tremors of 10^5 and 10^6 J did not constitute a direct hazard for conducted mining works.

Appearance of tremors of other type of focal mechanism II period of extraction was significant. It was a period of change of longwall run from NE-SW direction to E-W direction, that is period of so called 'slanting' of exploitation front. Geomechanical calculations showed that in the area of rockburst occurrence on 19.07.2011 layers situated over and under seam 510 in the area of longwall 6 were locally very strongly deformed causing compression of certain parts of rock mass. Analyses of tremors foci from the period preceding rockburst as well as in the next period indicated their non-shear but explosive character. It can be assumed that this type of tremor mechanism may have taken place as a consequence of a sudden loading of seam by overlaying roof strata which might have led to extreme conditions of load and to a dynamic burst of a part of a seam.

A complex analysis of geological and mining conditions, focal mechanism and local stress field may contribute to the development of mining seismology and in consequence to the increase of safety of carried out mining activities in conditions of high seismic hazard. It is substantial due to the costs connected with utilized rockburst prevention because the scope of preventive actions in a given region of exploitation ought to result from geomechanical analyses and seismologic observations.

Acknowledgments

I would like to thank employees of the Rockburst Department of the mine Bobrek-Centrum for their help with the analysis of geological and mining conditions and seismic activity as well as making seismograms of high-energy tremors available.

References

Aki K., Richards P.G., 1980. *Quantitative Seismology – Theory and Methods*. W. H. Frejman & Co., vol. 1, 2, San Francisco.

Angelier J., 2002. *Inversion of earthquake focal mechanisms to obtain the seismotectonic stress IV — a new method free of choice among nodal planes*. Geophys. J. Int. 150, 588-609.

Arnold R., Townend J., 2007. *A Bayesian approach to estimating tectonic stress from seismological data*. Geophys. J. Int., 170, 1336-1356.

Drzewiecki J., 2004. *Influence of the advance of longwall front on the dynamics of destruction of carboniferous rock mass* (in Polish). Scientific Works of the Central Mining Institute (GIG) no. 860, Katowice.

Dubiński J., Stec K., 2001. *Relationship between focal mechanism parameters of mine tremors and local strata tectonics*. Proc. Of 5 th International Symposium on "Rockburst and Seismicity in Mines" (eds. G. Van Aswegen, R.J. Durrheim, W.D. Ortlepp), SAIMM, Johannesburg, 113-118.

Fojtíková L., Vavryčuk V., Cipciar A., Madarás J., 2010. *Focal mechanisms of micro-earthquakes in the Dobrá Voda seismoactive area in the Malé Karpaty Mts. (Little Carpathians), Slovakia*. Tectonophysics 492, 213-229.

Gibowicz S.J., Kijko A., 1994. *Introduction to Mining Seismology*. Academic Pres, San Diego.

Katsumata K., Kosuga M., Katao H. and the Japanese University Group of the Joint Seismic Observations at NKTZ, 2010. *Focal mechanisms and stress field in the Atotsugawa fault area, central Honshu, Japan*. Earth Planets Space, 62, 367-380.

Kwiatek G., 2009. *Foci- Tensor of Seismic Moment – Spectral Parameters description of the programme www.sejsmologiagórnicza.pl/foci/*. (in Polish).

Makówka J., Kabiesz J., Dou Li-ming, 2009. *Relationship between the rock mass deformation and places of occurrence of seismological events*. Mining Science and Technology 19, 558-584.

Marcak H., 2012. *Seismicity in mines due to roof layer bending*. Arch. Min. Sci., Vol. 57 no. 1, p. 229-250.

McKenzi D.P., 1969. *The relation between fault plane solution and the directions of the principal stresses*. Bull. Seism. Soc. Am., Vol. 59, no 2.

Michael A.J., 1987. *Use of Focal Mechanisms to Determine Stress: A Control Study*. J. Geophys. Res., 92, 357-368.

Pangaea Scientific, 2007: MyFault program, www.pangaeasci.com.

Pasquale G., De Matteis R., Romeo A., Maresca R., 2009. *Earthquake focal mechanisms and stress inversion in the Irpinia Region (southern Italy)*. J. Seismol. 13, 107-124. DOI 10.1007/s10950-008-9119-x.

Reches Z., 1987. *Determination of the tectonic stress tensor from slip along faults that obey the Coulomb yield condition*. Tectonics, 6(6), 849-861.

Stec K., 2007. *Characteristics of Seismic Activity of the Upper Silesian Coal Basin in Poland*. Geophys. J. Int., Blackwell Publishing Ltd, V 168, 2007, p. 757-768.

Stec K., 2009. *Methods for Determination of Mechanism of Tremor Foci* (in Polish). Prace Naukowe GIG Górnictwo i Środowisko No. 4/1, Katowice:, p. 223-236.

Stec K., 2012. *Determination of Stress States in Zones with Seismic Hazard on the Basis of Parameters of the Mechanism of Tremor Foci* (in Polish). Przegląd Górniczy 2, 8-15.

Townend J., 2006. *What do Faults Feel?* Observational Constraints on the Stresses Acting on Seismogenic Faults, Earthquakes: Radiated Energy and the Physics of Faulting, Geophysical Monograph Series 170, 313-327.

Vicente G., Cloetingh A., Munoz-Martın A., Olaiz A., Stich D., Vegas R., 2008. *Inversion of moment tensor focal mechanisms for active stresses around the microcontinent Iberia: Tectonic implications*. Tectonics, Vol. 27, DOI:10.1029/2006tc002093, 1-22.

Zoback M.L., 1992. *First- and second-order patterns of stress in the lithosphere: The World Stress. Map project*. J. Geophys. Res., 97, 11,703-11,728.

Received: 17 May 2012