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NEW CRITERIA TO ASSESS SEISMIC AND ROCK BURST HAZARD IN COAL MINES

NOWE KRYTERIA DLA OCENY ZAGROŻENIA SEJSMICZNEGO I TĄPANIAMI W KOPALNIACH WĘGLA KAMIENNEGO

The paper presents new criteria of seismic and rock burst hazard assessment in Polish hard coal mines where longwall mining system is common practice. The presented criteria are based on the results of continuous recording of seismic events and analysis of selected seismological parameters: spatial location of seismic event in relation to mining workings, seismic energy, seismic energy release per unit coal face advance, ***b***-value of Gutenberg-Richter law, seismic energy index *EI*, seismic moment M_0, weighted value of peak particle velocity PPV_W. These parameters are determined in a moving daily time windows or time windows with fixed number of seismic tremors. Time changes of these parameters are then compared with mean value estimated in the analyzed area. This is the basis to indicate the zones of high seismic and rock burst hazard in specific moment in time during mining process. Additionally, the zones of high seismic and rock burst hazard are determined by utilization of passive seismic tomography method. All the calculated seismic parameters in moving time windows are used to quantify seismic and rock burst hazard by four level scales. In practice, assessment of seismic and rock burst hazard is used to make daily decision about using rock burst prevention activities and correction of further exploitation of monitored coal panel.

Keywords: mining seismology, rock burst, seismic event, seismic criterion, rock burst hazard assessment

Zagrożenie sejsmiczne i związane z nim genetycznie zagrożenie tąpnięciem w dalszym ciągu należą do najgroźniejszych zagrożeń naturalnych występujących w polskich kopalniach węgla kamiennego. W ostatnich latach w kopalniach Górnośląskiego Zagłębia Węglowego (GZW) rocznie rejestrowano 1000÷1500 wstrząsów o energii sejsmicznej $E_s \geq 1 \cdot 10^5$J (magnituda lokalna $M_L \geq 1.7$), a najsilniejsze z nich osiągały energię $E_s = 4 \cdot 10^9$J ($M_L = 4.1$). W latach 1991-2010 odnotowano w GZW 101 tąpnięć, z których około 66% miało miejsce w wyrobiskach chodnikowych, powodując ich uszkodzenia lub całkowite zniszczenie, a w niektórych przypadkach również wypadki śmiertelne. Przedstawiono podstawowe parametry sejsmologiczne stosowane w kraju i w świecie do oceny zagrożenia sejsmicznego. Opisano podstawowe zasady metody kompleksowej oceny stanu zagrożenia tąpnięciem, w skład której wchodzi metoda sejsmologiczna bieżącej (pomiarowej) oceny stanu zagrożenia.

Od wielu lat, wraz z ciągłym rozwojem bazy aparaturowej i możliwości w zakresie cyfrowej rejestracji sejsmogramów oraz przetwarzania i interpretacji danych pomiarowych wzrasta znaczenie metod

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sejsmicznych, które są dzisiaj powszechnie stosowane w polskich kopalniach zagrożonych tąpaniami. Ciągła obserwacja zjawisk sejsmicznych indukowanych w trakcie rozwoju procesu eksploatacji pokładów węgla umożliwiła, w oparciu o zgromadzoną bazę danych, opracowywanie nowych kryteriów zagrożenia sejsmicznego oraz zagrożenia tąpnięciem, które winny wyraźnie poprawić efektywność metody sejsmologii górniczej.

W artykule przedstawiono nowe kryteria oceny stanu bieżącego zagrożenia tąpaniami zaproponowane do stosowania w polskich kopalniach węgla kamiennego, które prowadzą eksploatację systemem ścianowym. Kryteria te są oparte na wynikach ciągłej rejestracji sejsmologicznej, połączonej z bieżącą analizą zarejestrowanych wstrząsów i obliczaniem wybranych parametrów sejsmologicznych. Parametry te to położenie ognisk wstrząsów w stosunku do wyrobisk eksploatacyjnych, energia sejsmiczna wstrząsów, suma energii sejsmicznej wyzwolona na każde 5m postępu ściany eksploatacyjnej, wartość wagowanego parametru amplitudy prędkości drgań PPV_W, moment sejsmiczny M_0, indeks energii EI oraz parametr ***b*** rozkładu wstrząsów według relacji Gutenberga-Richtera. Wartości powyższych parametrów są określane dla każdej doby lub w przesuwających się co dobę oknach czasowych lub oknach zawierających określoną liczbę wstrząsów, a następnie porównywane, raz na dobę, z ich wartościami średnimi wyznaczonymi dla obserwowanego rejonu eksploatacji lub z opracowanymi wartościami kryterialnymi. W ten sposób wyznaczane są, dla danego momentu czasu, strefy w których możne wystąpić potencjalnie wysokie zagrożenie sejsmiczne i zagrożenie tąpaniami. Ponadto, w strefach o podwyższonym naprężeniu oraz w strefach o skomplikowanej sytuacji górniczo-geologicznej, charakteryzujących się zaszłościami starej eksploatacji oraz zaburzeniami geologicznycmi, wykonywane są dodatkowo doraźne obliczenia pola prędkości fal sejsmicznych z wykorzystaniem metody tomografii pasywnej. Należy podkreślić, że wszystkie obliczane wartości powyższych parametrów są skwantyfikowane i określają wartości kryterialne w czterostopniowej skali oceny stanu zagrożenia sejsmicznego i zagrożenia tąpnięciem (tabela 2).

Stopnie zagrożenia zostały skwantyfikowane w oparciu wyniki pomiarów sejsmologicznych wykonywanych na bieżąco w sposób ciągły i są wyrażone w formie kryteriów empirycznych, opracowanych na podstawie analizy dużego zbioru danych sejsmicznych oraz obserwacji makroskopowych w wyrobiskach górniczych. Należy podkreślić, że w czasie występowania wysokich stanów zagrożenia sejsmicznego lub zagrożenia tąpnięciem, opracowana metoda pozwala wyznaczyć obszary o podwyższonym stanie zagrożenia, umożliwiając zaprojektowanie i zastosowanie odpowiedniej w miejscu i czasie profilaktyki tąpaniowej.

Ważnym aspektem w ocenie stanu zagrożenia sejsmicznego i tąpaniami jest problem ciągłego przemieszczania się stref zagrożenia (stref podwyższonych naprężeń) w czasie prowadzonej eksploatacji. Dla uchwycenia nie tylko miejsc potencjalnego zagrożenia, ale również określenia w jakim momencie czasu pojawia się strefa potencjalnego zagrożenia, zaproponowano analizę parametrów kryterialnych w przesuwających się oknach czasowych z dobowym raportowaniem wyników.

W artykule przedstawiono dotychczasowe kryteria oceny stanu zagrożenia tąpnięciem – tabela 1 (Barański i in., 2007), stosowane aktualnie przez większość kopalń w polskim górnictwie węglowym. Kryteria te w części przypadków nie prowadziły do zadawalających i w pełni wiarygodnych wskazań, ze względu na małą liczbę analizowanych parametrów sejsmologicznych oraz brak sekwencyjnej analizy ich zmian w czasie prowadzonej eksploatacji. Wady te uwzględnia nowe podejście metodyczne do oceny stanu zagrożenia. Nowe kryteria oceny stanu zagrożenia sejsmicznego i zagrożenia tąpnięciem przedstawiono w tabeli 2. Zakwalifikowanie do określonego stanu zagrożenia wymaga spełnienia wartości kryterialnych przez więcej niż połowę parametrów sejsmicznych, przypisanych do określonego stanu zagrożenia i rodzaju wyrobiska.

Skuteczność przedstawionych nowych kryteriów oceny stanu sejsmicznego i zagrożenia tąpnięciem, opartych o sekwencyjną analizę wybranych parametrów kryterialnych w przemieszczających się co dobę oknach czasowych, została pokazana na przykładach obliczeniowych rzeczywistych sytuacji pomiarowych uzyskanych podczas eksploatacji pokładu węgla 510 ścianą nr. 6 oraz pokładu 503 ścianą nr. 3 w KWK Bobrek-Centrum.

Przeprowadzono dyskusję opracowanych kryteriów dowodząc, że stosowanie do oceny stanu zagrożenia tąpaniami różnych parametrów wstrząsów jest niezbędne, aby na bieżąco obserwować to zagrożenie w zależności od różnych mechanizmów wstrząsów i dla różnych sytuacji górniczo-geologicznych. Analiza jednego parametru kryterialnego może często doprowadzić do błędnych wniosków i niskiej wiarygodności wykonanej oceny stanu zagrożenia. Z tej przyczyny w najnowszej wersji metody sejsmologicznej zaproponowanej do stosowania w polskich kopalniach węgla kamiennego, uwzględniono pięć niezależnych parametrów sejsmologicznych opisanych w tabeli 2.

Słowa kluczowe: sejsmologia górnicza, tąpnięcie, wstrząs sejsmiczny, kryterium sejsmiczne, ocean zagrożenia tąpnięciem

1. Introduction

Seismic risk and related to it rock burst hazard belong still for the most dangerous hazards occurring in the Polish hard coal mines. In recent years in the mines of the Upper Silesian Coal Basin (the USCB) 1,000÷1,500 tremors of seismic energy $E_s \geq 1 \cdot 10^5$J (local magnitude $M_L \geq 1.7$) were recorded per year and the strongest of them reached energy of $E_s = 4 \cdot 10^9$J ($M_L = 4.1$), (Stec, 2007). In the years 1991-2010, 101 rock bursts in the USCB were recorded. Approximately 66% of rock bursts occurred in roadway workings (Bukowska, 2012), causing damage or complete destruction and in some cases, fatal accidents. The rock burst hazards in the USCB are strongly influenced by the remnants of the old coal mining and tectonic faults located in the immediate vicinity of mining activity. The hazards are influenced as well by the depth of exploitation and rock mass strength parameters – especially post-critical parameters of rocks and extracted coal seam (Bukowska, 2013). The rock burst hazard also occur in other world mining regions, e.g. in the nearby Ostrava-Karviná Coal Basin (Konecny, 1989), in German coal basins (Bischoff et al., 2010) and in the coal basin areas of the US, China, South-African, Russian, Australian, Canadian and other. In the USCB the seismic hazard in the form of strong tremors, besides the above mentioned rock burst hazard, has a significant impact on urbanized surface of mining areas. The occurring ground motions are characterized by a high intensity of vibration and can cause damage to buildings and costs associated with their repair, as well as a nuisance for residents. Numerous preventive methods and technologies have been developed in Poland. Methods are used at recognizing and assessing of seismic and rock burst hazards. The aim of employing such methods is to combat or reduce intensity of rock burst as well (Dubiński & Konopko, 2000; Pytlik, 2013; Cała et al., 2013; Rotkegel, 2013). An extremely important role, especially in the recognizing and assessment of these hazards, is played by the geophysical methods, among which dominate microseismological observation and their interpretation and analysis (McGarr et al., 1981; Gibowicz & Kijko, 1994; Mendecki, 1997). The importance of seismic methods have risen from many years together with the continuous development of research equipment and capabilities in the field of digital seismograms recording and the processing and interpretation of measurement data. These methods are widely used in Polish mines which are prone to the rock burst hazard. Continuous observation of seismic events induced by mining enabled to develop new criteria for seismic and rock burst hazard. The new criteria should improve the efficiency of methods used in mining seismology.

2. The current state of rock burst hazard assessment based on the continuous seismic observation

It is assumed that seismic parameters on which the assessment of seismic and rock burst hazard criteria are based should show their dependence on the mechanism of seismic sources, as well as the ability to cause damaging effect in mine workings. Research in this area, both Polish and foreign, indicate the following basic source mechanisms of mining seismic events and rock bursts occurring in underground coal mines (e.g. Brady & Brown, 1985; Idziak, 1999; Drzewiecki, 2001; Stec, 2007; Zipf, 2007; Wehling-Benatelli et al., 2012; Marcak & Mutke, 2013; Lizurek et al., 2015) :

- Seismic source mechanism is resulted from overstressed zones in coal seam – there is an immediate release of energy in the coal seam in the vicinity of the coal face-line, especially in zones of increased stress; these tremors frequently are characterized by an explosive or implosive mechanism or by uniaxial compression or tension (mining induced seismic events),

- Hypocenter of seismic events are occurring above or below the extracted panels – seismic source mechanisms are connected with the rock-mass strata fracturing located around the face-lines position. The cracks or delamination of these rock layers take place mostly in the high stress zones related to mining operation. Seismic source mechanism is described herein by uniaxial tension or compression or by shearing mechanism (mining induced seismic events),
- Seismic sources are located in the fault zones – there is a dynamic displacement of rock mass on the fault plane, especially where sites appear unstable (tectonic stresses) and are activated by the change of the stress conditions induced by mining activities; seismic events are strongest ones (local magnitude from 3 to 5) and are characterized in most by shearing failure source mechanism (seismic events triggered by mining – fault reactivation).

In the case of mining induced seismic events directly in coal panel, the strongest of them are often the direct cause of rock burst phenomena. In the case of seismic events located in rock-mass strata or on tectonic fault, the rock burst in operating workings is triggered by a wave vibrations related to seismic events located outside of the extracting panel. The near wave field of tremor induces a strong impulse in a form of a stress wave. Thus, when the mine working is in the interaction zone of high dynamic stresses associated with the seismic waves and high static stress, it may cause rock burst in this area. The mechanism of the rock burst in this case is related to explosion (implosion) of a coal seam in the immediate vicinity of the mine openings and the rocks are being thrown dynamically into the excavation or the coal floor is heaved (Dubiński & Mutke, 1996). This rock burst mechanism is currently the most common in Polish underground coal mines. It shows that the rock burst hazards assessment criteria must relate to the seismic hazard assessment, knowledge of parameters describing the source mechanism of seismic events and values of peak particle velocity motion *(PPV)* in the vicinity of operational workings. In addition, the current information about the location of high stress zones in the vicinity of the coal face and roadways is important, as well as monitoring of current seismic hazard level.

2.1. Continuous seismic observation

The continuous seismic monitoring of extracting coal panel should automatically record the seismic events as well as should allow on processing and analysis data in almost on-line mode. Seismological network should provide registration of seismic sensors close deployed around the active mining area and also located at a long distance. This network geometry allows for observation of complete set of seismic events from a low-energy level and allows for registration of vibration in near and far wave field. Specially designed geophone probes are spark-proof and mobile, which means that they can be easily moved (depending on the mining conditions) and can record without clipping very high values of velocity vibration amplitudes *PPV*. The software of the seismic system allows for the 3D location of seismic events hypocenter, determination of seismic source parameters and monitoring of particle velocity vibration in mine openings localized in both far and near wave field. Such assumptions fulfills the Seismic Observation System (acronym: SOS GIG), used in a number of Polish coal mines for assessing the seismic and rock burst hazard. SOS GIG seismic equipment is also used in a number of Chinese mines. In Republic of South Africa and in many other countries around the world the ISS system is very popular (Mendecki, 1997).

2.2. Basic seismic parameters

Geophysical methods are widely used in mining in terms of monitoring and evaluation of seismic hazard and therewith associated rock burst hazard. They are used to solve various rock mechanics and geohazard tasks in terms of the mining impact on the rock mass structure (Hatherly, 2013). Methods used for the on-going registration of a dynamic effects of rock mass fracturing related to the seismic emission, are currently widely used to assess of seismic and rock burst hazards. This takes place both in the worldwide and Polish mining industry. There has been a systematic development of equipment and observation networks to monitor mining induced seismicity, including the development of software for rapid interpretation of the recorded seismic phenomena. As a result, a routine procedure for processing the recorded seismic events allows for the on-going creation of seismic catalog, including such data as: date, time and location of tremor, seismic moment and seismic energy, stress drop in the seismic source, the source radius, etc. (Mendecki, 1997). Cracks, delamination and displacement of rock masses cause inelastic deformation in a certain volume of rocks, which causes a sudden release of energy in the form of seismic wave's emissions. It turns out that these waves contain in their structure useful information about the dynamic processes induced by mining operations, and thus allow for the determination of important parameters of seismic hazard assessment. It should be emphasized that an extensive study on the criterion of rock burst hazard was performed in deep mines in Republic of South Africa, United States, Russia and Europe. The new criterial values of these parameters have been developed and validated. They contain useful information about the hazard, for example the seismic energy index, *EI* – which is the ratio of the observed seismic energy to the average energy emitted by seismic events at the same seismic moment (Van Aswagen & Butler, 1993). Important research related to monitoring and assessing of *PPV* in the near wave field led, among others, McGarr et al. (1981) and Dubiński & Mutke (1996). Intensive work was also undertaken in regard to location the hypocenter of mining seismic events (Gibowicz & Kijko, 1993) and to use the passive tomography to study the seismic wave velocity distribution images in order to seismic hazard assessment in mines (Maxwell & Young, 1993; Lurka 2002).

Numerous studies also concern the parameters assess of Gutenberg-Richter distribution (Gutenberg & Richter, 1954) for seismic events induced by mining (Holub, 1995; Mutke & Pierzyna, 2010; Kwiatek et al. 2011), primarily in terms of verifying the possibility of extending the G-R relation to the set of seismic events with low magnitudes.

In the case of seismic events located in the coal bed or in hard rock directly above or below the extracted coal panel, seismic activity is an important indicator of high stress zones. This is particularly important if various stress concentration factors (pillars, edges, remnants) are present (Dubiński, 1989).

Empirical observation of the rock bursts phenomena in Polish coal mines suggest that the destruction in operating workings usually occurred when the hypocenter of seismic events were located near the damaged workings and seismic energy was higher than $1 \cdot 10^5$J (local magnitude, $M_L > 1.7$) (Mutke, 2008).

2.3. The present principles of the seismic and rock burst hazard assessment in Polish mines

Due to the different mechanisms of rock bursts and a limited range of observation with different measuring methods, assessment of hazards made by various methods may differ significantly from each other. Certainly, significantly more objective assessment of the rock burst hazards can be achieved by simultaneous research. This research can be carried out by several methods in the coal bed and in the rock-mass surrounding the coal bed and through using a comprehensive interpretation of their indications (Barański et al., 2007). From the above mentioned reasons, the comprehensive rock burst hazard assessment methodologies were created. The composition of this methods include a variety of detailed methods, appropriate for determining the state of rock burst hazards both from coal bed and from rock-mass strata. The method of assessing the potential state of rock burst hazard is based on an interpretation of geological and mining factors in the mining area. The chosen on-going monitoring methods are supported on equipment ready to use in industrial scale.

The comprehensive method consists of the following detailed methods (Dubiński & Konopko, 2000):

a) diagnosis of mining and geological factors allows for assessment of the potential tremor hazard due to the geotechnical properties of the coal bed and the rock mass, deposit stratification conditions, the influence of previous mining activities, etc.,
b) continuous seismological observation allows determining the current state of rock burst hazard (monitoring of an emergency state) based on registration of rock mass tremors;
c) continuous seismoacoustic emission enables the observation of changes in level of cracks in the coal bed through the registration of low-energy phenomena associated with the overstressed zones:
d) probes drilling in coal bed allow evaluating the state of stress in coal seam based on the yield of drillings;
e) other methods – in justified cases – to assess the actual state of rock burst hazards (passive tomography, active seismic survey, etc).

Assessment of the rock burst hazard indicates the directions for the mining activities in the evaluated coal panel:

a) mine workings with lack of rock burst hazard (hazard level „**a**")
   – all works can be carried out in accordance with established technology.
b) mine workings with low rock burst hazard (hazard level „**b**")
   – all works can be carried out in accordance with established technology,
   – enhanced supervision should be used on observations of the state of rock burst hazard and of mining technology.
c) mine workings at medium rock burst hazard (hazard level „**c**")
   – further driving of the working should be performed with use of a prevention method established for such hazard state. The work is done with ongoing analysis of the results of control measurements for at least once a day and without further growth of hazard.
d) mine workings with high rock burst hazard (hazard level „**d**")
   – mining must be stopped, and the crew must immediately withdraw in a safe place,
   – mining manager should determine the methods of limiting the hazard state. The methods controlling the effectiveness of prevention should be used. The number of the workers involved in prevention work in the mining area should be specified.
   If the „**d**" hazard level is kept, only works to reduce the hazard may be conducted.

Of above mentioned measuring methods, forming the comprehensive method, the seismological method is currently the most widely used in the Polish mines in the context of the current assessment of seismic and rock burst hazard. This method is described in the the form of instruction "*Mining seismology method for rock burst hazard assessment*" (Barański et al., 2007). It is based on analysis of the seismic activity recorded under continuous observation and continuous passing of this information to the mine's management, and reporting results every 24 hours. The essence of the method is not only the registration of rock mass tremors and their detailed analysis, but primarily the development for a better recognition of the relationship between seismic activity and the rock burst hazard. Assessment of the rock burst hazard is carried out using the current observation of a monitored rock mass seismicity occurring in the mine openings area. This is done by determining the resulting hazard increase or decrease in comparison with the current hazard state. Determination of rock burst hazard levels by seismological methods (**a** – lack of hazard, **b** – low hazard, **c** – medium hazard, **d** – high hazard) is performed using the seismic parameters obtained in the area of openings (the range of seismic energy, the maximum seismic tremor energy, the sum of seismic energy for 5 m coal face advance – Table 1).

Table 1 shows the quantitative criteria of the current assessment of seismic and rock burst hazard presently used in Polish hard coal mining industry.

TABLE 1

Quantitative assessment of the rock burst hazard according to the observed seismicity in the mining activity area (Baranski et al., 2007)

Hazard level	Longwalls face position area	Roadways
a lack of hazard	1. Lack of tremors or very few with a seismic energy: 10^2J÷10^3J; $E_{max} < 10^4$J 2. $\Sigma E < 10^5$J per 5 m of coal face advance	1. Lack of tremors or very few with a seismic energy level 10^2J; $E_{max} < 10^3$J 2. $\Sigma E < 10^3$J per 5 m of operation
b low hazard	1. Tremors with seismic energy : 10^2J ÷10^5J; $1 \cdot 10^4\text{J} \le E_{max} \le 5 \cdot 10^5$J 2. $1 \cdot 10^5\text{J} \le \Sigma E < 10^6$J per 5 m of coal face advance	1. Very few tremors with seismic energy level 10^2J÷10^3J; $E_{max} \le 5 \cdot 10^3$J 2. $1 \cdot 10^3\text{J} \le \Sigma E < 10^4$J per 5 m of operation
c medium hazard	1. Tremors with energy magnitude 10^2J÷10^6J; $5 \cdot 10^5\text{J} < E_{max} \le 5 \cdot 10^6$J 2. $1 \cdot 10^6\text{J} \le \Sigma E < 10^7$J per 5 m of coal face advance	1. Tremors with seismic energy level 10^2J÷10^4J; $5 \cdot 10^3\text{J} < E_{max} \le 5 \cdot 10^5$J 2. $1 \cdot 10^4\text{J} \le \Sigma E < 10^5$J per 5 m of operation
d high hazard	1. Tremors with energy magnitude 10^2J÷10^6J; $E_{max} > 5 \cdot 10^6$J 2. $\Sigma E \ge 10^7$J per 5 m of coal face advance	1. Tremors with seismic energy level 10^2J÷10^5J; $E_{max} > 10^5$J 2. $\Sigma E \ge 10^5$J per 5 m of operation

where: E_{max} – maximum energy of seismic event registered in the last 24 hours, J.

The additional measurements or analysis are performed in zones with increased seismic hazard. In practice, the additional measurements include in-seam seismic tomography and passive tomography methods. The results of the seismic observations are filled up once a day to "The rock burst hazard state and prevention activity daily report".

3. New criteria for the seismic and rock burst hazard assessment

From several years, there has been a clear development of equipment base and consequent increase in the possibilities for the processing and interpretation of recorded data in Polish hard coal mining industry (SOS GIG seismic system). The mining seismological network consisting of modern one and three axis 1 Hz geophone probes DLM 2001, enable to continuous full registration of tremors of energy from $E_s \geq 1 \cdot 10^2$ J. The software allows determining 3D source location of recorded seismic events and calculating the seismic energy. It also includes the assessment of the seismic source parameters (scalar seismic moment, stress drop in the seismic source, the energy index *EI*, ***b***-value of G-R law and velocity tomograms using passive tomography techniques.

Having the foregoing, the new measurement and interpretive capabilities, based on the results of numerous measurements and field tests, the new version of seismic and rock burst hazard assessment criterion was developed. The new criterion is described in Central Mining Institutes Instruction No 22 "*The principles of mining seismology for seismic and rock burst hazard assessment*" (Barański et al., 2012). The application of new method requires a more sophisticated interpretation and processing routines. New criterion refers to the previous four-level scale of seismic and rock burst hazard assessment. Further important feature is not only to include the above-mentioned new seismic parameters, but also the observation of changes in the appropriately selected time windows moving every 24 h.

3.1. The criterial parameters of seismic hazard assessment in Polish coal mines based on seismological observations

For the assessment of seismic and rock burst hazard using new seismic parameters it is proposed to use such values as:

- location of tremor hypocenter (*X*, *Y*, *Z*),
- seismic energy (magnitude) of seismic event or seismic moment,
- the total seismic energy released for every 5 m of the longwall coal face advance,
- change of the ***b***-value in a moving time window,
- weighted value of peak particle velocity (PPV_W) parameter in workings localized in exploitation area,
- seismic energy index, *EI*,
- tomographic velocity image obtained for recorded seismic events (complementary method).

The proposed new seismic criteria include the so far used criteria and additional criteria developed for a several new seismic parameters, defined in daily moving window. From the perspective of engineering practice, the current assessment of seismic and rock burst hazard, which is a deterministic approach, is currently the only possible one for industrial use in conditions of underground mining activities.

3.2. The criterion for assessing the rock burst hazard level

The new criteria for assessing the rock burst hazard level are presented in Table 2. Qualification for a specific hazard level requires that more than half of the seismic criteria must be met. For example, for "**d**" hazard level in roadways at least 3 seismic criteria at four assigned in Table 2 must be met. In case of longwall faces, at least 3 seismic criteria at five assigned also must be met.

TABLE 2

New principles of quantitative assessment of the seismic and rock burst hazard level according to the observed seismicity in the mining activity area

Hazard level	**Mine workings**	**Seismic criteria**	**Seismic characteristics**
a lack of hazard	longwalls	tremors with energy magnitude $10^2 \div 10^3$ J, occasionally 10^4 J. $\sum E < 10^5$ J per 5 m of coal face advance PPV_W in **a** hazard level Parameters M_0, EI and ***b***-value do not indicate increase of hazard (level **a** and **b** – at least two in **a** state)	Low seismicity, lack of damaging effects
	roadways	Without tremors or individual tremors with energy $< 5 \cdot 10^3$ J PPV_W in **a** hazard level	
b low hazard	longwalls	tremors with energy magnitude $10^2 \div 10^4$ J, occasionally 10^5 J $1 \cdot 10^5 \le \sum E < 10^6$ J per 5 m of coal face advance PPV_W in **b** hazard level Parameters M_0, EI and ***b*** – value do not indicate increase of hazard (level **a** and **b** – at least two in **b** level)	Medium seismicity, lack of damaging effects, in the workings area seismic events are felt by the miners
	roadways	tremors with energy $< 5 \cdot 10^4$ J PPV_W in **b** hazard level Parameters M_0, EI and ***b***-value do not indicate increase of hazard (level **a** and **b**, at least two in **a** level)	
c medium hazard	longwalls	tremors with energy magnitude $10^2 \div 10^6$ J $1 \cdot 10^6 \le \sum E < 10^7$ J per 5 m of face advance PPV_W in **c** hazard level Parameters M_0, EI and ***b***-value indicate increase of hazard (at least two in **c** level and none in **d** level)	High seismicity, rock mass relaxation occurs with the effects not decreasing the stability and functionality of the workings support; in the workings area seismic events are highly felt by the miners
	roadways	tremors with energy magnitude $10^2 \div 10^4$ J, occasionally 10^5 J PPV_W in **c** hazard level Parameters M_0, EI and ***b***-value indicate increase of hazard (at least two in **c** level and none in **d** level)	
d high hazard	longwalls	tremors with energy magnitude $10^2 \div 10^6$ J, occasionally $E \ge 10^7$ J $\sum E \ge 10^7$ J per 5 m of progress PPV_W in **c** or **d** hazard level Parameters M_0, EI and ***b***-value indicate increase of hazard (at least two in **c** level and one in **d** level)	Very high seismicity, rock mass relaxation occurs, in the workings area shocks are highly felt by the miners
	roadways	tremors with energy magnitude $10^2 \div 10^5$ J, occasionally $E \ge 10^6$ J PPV_W in **c** or **d** hazard level Parameters M_0, EI and ***b***-value indicate increase of hazard (at least two in **c** level and one in **d** level)	

The increased of seismic and rock burst hazard level (level **b**, **c** and **d**) is specified on the basis of seismological observation and is valid for 24 hours after the assessment. The reduction of rock burst hazard level is done gradually by a maximum of one degree on every 24 hours.

The local deviation of criteria values can be elaborated by the mine itself. It should be based on the back analysis of tremors, recorded by the mine seismological network or based on other experiences. As an example of local, specific criteria values can serve the quantitative classification of the seismic and rock burst hazard level in Bobrek coal mine, based on the anomaly coefficient of ***b***-value, which is defined as follows:

$$A_{G\text{-}R} = [(b_S - b)/b_S] \cdot 100\% \tag{1}$$

where:

- b — a momentary value of ***b*** parameter, calculated for tremors recorded within a specified time window,
- b_S — a mean value of ***b*** parameter calculated from whole entire catalog of tremors for the whole area of the mine or the selected area of exploitation.

The criteria values developed for the operating conditions in the Bobrek mine are shown in Table 3 (Pierzyna, 2014).

TABLE 3

The local criterion for seismic hazard level at Bobrek mine using the ***b***-value of Gutenberg-Richter law and anomaly coefficient

Hazard level	$A_{G\text{-}R}$ anomaly, %	***b***-value
a lack of hazard	$A_{G\text{-}R} < 0$	$\boldsymbol{b} > \boldsymbol{b_S}$
b low hazard	$25 > A_{G\text{-}R} \geq 0$	$\boldsymbol{b} \leq \boldsymbol{b_S}$
c medium hazard	$50 > A_{G\text{-}R} \geq 25$	$\boldsymbol{b} < \boldsymbol{b_S}$
d high hazard	$A_{G\text{-}R} \geq 50$	$\boldsymbol{b} < \boldsymbol{b_S}$

Very high values of the $A_{G\text{-}R}$ anomaly parameter should correlate with the preparation of rock strata to the release of greater number of strong seismic events. Negative values of the $A_{G\text{-}R}$ anomaly parameter should indicate the lower seismic hazard in the mining activity area.

4. Verification of the new seismic and rock burst hazard assessment criteria on field testing areas

In the presented new approach on the assessment of seismic and rock burst hazard it is necessary to carry out a continuous seismic monitoring (monitoring the tremors and interpretation of seismic data). On the basis of the level of criterial seismic parameters the status of hazard is daily estimated. These criteria are developed on the basis of analysis of a large set of seismic data and macroscopic observation in mine workings. It should be emphasized that, during the occurrence of high seismic or rock burst hazard conditions, developed method allows to determine the zones with the increased hazard level. This allows for a design and application of the rock burst prevention in appropriate time and place.

The verification of the developed criteria based on the actual situation and measurement obtained during the extraction of the 510 coal seam in longwall panel No 6 and the 503 coal seam in longwall panel No 3 in Bobrek-Centrum coal mine is shown in this chapter. The coal panel No. 6/510 was extracted in conditions of high rock burst hazard. The seismic observations were performed in the period from 06/30/2011 to 10/10/2011. During that time 285 seismic events were recorded with the following energy distribution: 90 tremors of magnitude 10^2J, 123 of magnitude 10^3J, 57 of magnitude 10^4J, 11 of magnitude 10^5J and 4 of magnitude 10^6J – including tremor, which caused the rock burst in the longwall panel No. 6, on 07/19/2011 at 6:06 PM and seismic energy, $E = 8 \cdot 10^6$J. As a result of rock burst the extraction process was stopped for more than a month. Restarting the longwall panel took place on 09/01/2011. Mining of coal panel No 3/503 was carried out at a depth of about 700 m and ran in the tectonic discontinuity located in Bytom through axis. It should be mentioned that the Bytom through axis in the past also recorded a strongest seismic events with energy range of $1 \cdot 10^8 \div 3 \cdot 10^9$J. Also during mining of longwall panel No. 3 in 503 coal seams, the strongest tremor occurred when coal face approached to the axis of the Bytom through. The tremor of seismic energy $E = 8 \cdot 10^8$J was registered on 12/16/2009 and was localized on depth of 945m ppm; this is about 500 m under the 503 coal seam. Extraction of this seam was accompanied by a high seismic activity (4722 tremors, including 570 high energy, i.e. of seismic energy $E > 1 \cdot 10^5$ J ($M_L > 1.7$). A detailed description of the geological-mining and seismological conditions on these testing areas for the panel 6/510 can be found in doctor thesis publication (Pierzyna, 2014) and for the panel 3/503 in the article written by Marcak & Mutke (2013).

4.1. Verification of the *b*-value and $A_{G\text{-}R}$ anomaly criterion

For the determination of the Gutenberg-Richter relationship and the calculation of the ***b***-value of this relationship, together with an estimation of the standard deviation using method of maximum likelihood (Utsu, 1965), the software "GMB" was developed. In Fig. 1 can be seen that several days before the rock burst phenomena a trend of sequential decreasing of ***b***-value is observed. The ***b***-value decreased between the values of 1.1 on 07/04/2011 to the value of 0.75 on the day of rock burst that is, 07/19/2011.

Examining the trend changes of the ***b***-value computed in 15-day moving time windows shifted once a day has proved that extremely useful information about rock burst hazard level was obtained. The anomaly of this parameter before the rock burst was 52% in relation to the average values of this parameter for the "Bobrek" mine, which indicates that the value of the seismic anomaly $A_{G\text{-}R}$ indicated a high level of seismic and rock burst hazard, according to the criterion presented in the table 3.

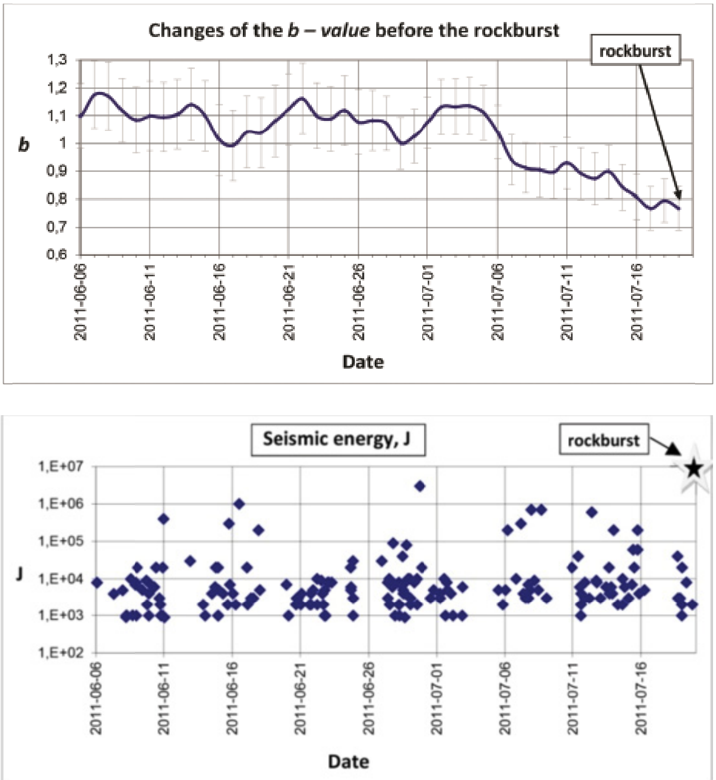

Fig. 1. Distribution of the ***b***-value of Gutenberg-Richter law for tremors from the 6/510 longwall panel registered before the rock burst accident in regards to seismic activity

4.2. Verification of the *EI* criterion

The *EI* parameter was developed by Van Aswegena and Butlera in 1993 (Mendecki,1997):

$$EI = \frac{E}{\bar{E}(M_o)} \tag{2}$$

where:

$\bar{E}(M_o) = 10^{c \log M_o - d}$,

c, d — constant for given area,

M_o — scalar seismic moment.

This parameter expresses the ratio of seismic energy of recorded tremor to the average energy released in the study area, of the tremors from the same seismic moments. From Van Aswegen and Butler (1993) study follows that if an Energy Index parameter, $EI > 1$ it states that stress in the hypocenter area is higher than the average for the analyzed area. Therefore, this parameter informs about running mining in areas of high seismic hazard. An example of an *EI* parameter distribution during mining activity is shown in Figure 2. The analyzed data was obtained from seismic data recorded during the operation of longwall panel No. 3/503. The strongest tremor, with seismic energy $E = 8 \cdot 10^8$J ($M_L = 3.7$) occurred during mining of this panel on December 16, 2009. In the period of November-December other severe tremors were recorded from the extracted coal panel No. 3/503. The highest value of the *EI* parameter with magnitudes of 4÷5 order was recorded during higher seismic activity recorded at this panel.

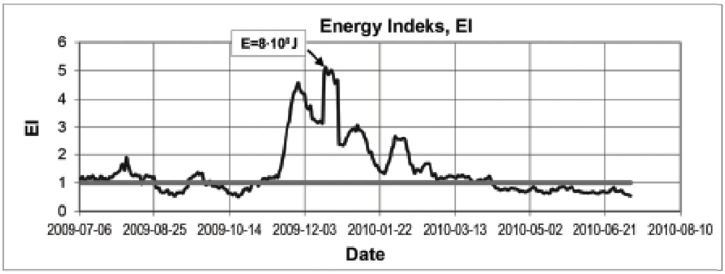

Fig. 2. An example of sequential distribution of *EI* parameter in moving time windows with the progress of 1 day in coal panel no. 3/503. On December 16, 2009 the strongest tremor of seismic energy $E = 8 \cdot 10^8$J ($M_L = 3.7$) occurred at a time when was the highest value of *EI* parameter

4.3. Verification of the passive seismic tomography method

The tomographic calculations were performed with assumption that the seismic wave propagates along the bent seismic rays and reflects better the propagation of seismic waves in heterogeneous medium in comparison with the straight line wave propagation (Lurka, 2009).

Figure 3 shows bent-ray tomographic velocity image in the area of coal panel 6 in seam 510 in Bobrek-Centrum mine. The underground seismic network consisted of 32 seismic stations. Tomographic velocity image were obtained for seismic events recorded between 06/15/2011 and 07/15/2011. Only seismograms with at least 5 picked arrival times of seismic P wave were taken into consideration. The location of the strong seismic tremor that caused rock burst on July 19th 2011 and location of the damaged mine workings was shown in fig. 3. The strong seismic event with seismic energy $E = 6 \cdot 10^6$ J was located in the zone of strong velocity gradient. Tomographic velocity image were obtained from seismic events recorded during one month before the rock burst occurrence. The damaging effect of rock burst took place also in the velocity gradient area i.e. between lower and higher velocity values (Fig. 3). This confirms the observation that zones of higher seismic velocity gradients correlate with high energetic seismic events (Maxwell & Young, 1996; Mutke et al., 2001; Lurka, 2002).

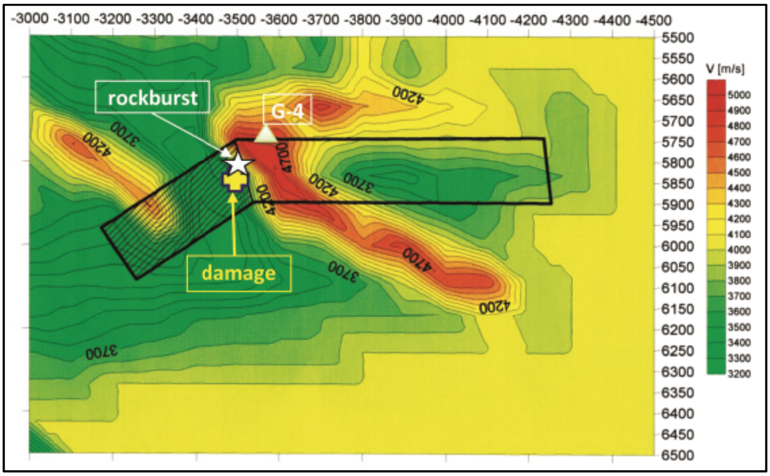

Fig. 3. Bobre mine, coal panel no 6/510. Tomographic velocity image (m/s) calculated from seismic events recorded between June 15th 2011 and July 15th 2011. The star mark shows the epicenter of strong seismic tremor with seismic energy $E = 8 \cdot 10^6$J; the cross mark depicts location of damaged mine workings due to rock burst in coal seam

4.4. Peak particle velocity parameter in vicinity of operational workings – *PPV* method

The increase of PPV_W parameter in sequential images and its approaching to the criterion value of 0.05 m/s is information about the occurrence and increase of the hazard. The PPV_W parameter denote the weighted value of *PPV*, to take into account the values transferring the main part of seismic energy. The use of weighted value of PPV_W eliminates high values of *PPV*, which are not relevant to the damaging response of the underground mine working on dynamic load.

The *PPV* values are recorded by the velocity sensors and then weighted. The PPV_W parameters are plotted in almost real time and compared to established PPV_W criteria. The elaborated criterion of weighted PPV_W parameter, for level of seismic and rock bursts hazard assessment regarding to evaluation of the stability of excavation is as follows:

a – lack of hazard: $PPV_W \leq 0.05$ m/s
b – low hazard: $0{,}05 < PPV_W \leq 0.2$ m/s
c – medium hazard: $0{,}2 < PPV_W \leq 0.4$ m/s
d – high hazard: $PPV_W > 0.4$ m/s

for seismic energy $E_s > 1 \cdot 10^5$ J and frequency of vibration $f < 40$ Hz.

For the rock burst phenomena on July 19th 2011 and of seismic energy $E_s = 6 \cdot 10^6$ J that caused damage to the mine workings and injured three people, the measured value of the weighted parameter on the measuring station 4, was $PPV_W = 0.098$ m/s at distance of 143 m from the epicenter of the tremor. Given the distance of the tremors epicenter from the place of the observed effects, d = 45 m, the calculations show that in the considered place $PPV_W = 0.410$ m/s. Therefore it can be classified that tremor took place in an area of high level of rock burst hazard, **d**, according to the criteria stated in Table 2.

Assessment of the effectiveness of certain criterial parameters, can also be found in the literature (Mutke & Pierzyna, 2010; Dubiński & Mutke, 2012).

5. Discussion

Seismicity induced by underground mining can have different genesis and different mechanisms of seismic sources. Therefore, potential precursors of strong seismic events can be completely different. For example, in the case of seismic tremors with hypocenters located in overstressed coal seam zones high-frequency seismic events and high PPV_W values are relevant. Seismic events related to tectonic faults and other geological structures with hypocenters away from mining excavations have relatively low PPV_W values. Seismic tremors located on active tectonic faults have usually high seismic energies, but due to the large distance from excavations its seismic vibrations are attenuated and usually do not have significant impact on stability of underground mining workings. On the other hand seismic events located in coal seam may produce vibrations dangerous to underground workings.

Rock burst hazards assessment using seismic parameters is essential to monitor the hazard in real time from various types of tremors. Seismic hazard criterion based on analysis of one seismic parameter can lead to wrong or low quality estimation of seismic and rock burst hazard. For this reason, the new seismic hazard criteria currently used in Polish coal mines utilize 5 independent seismic indication: level of seismic activity, seismic energy release per unit coal face advance, a group of three parameters (***b***-value of Gutenberg-Richter law, energy index *EI*, seismic moment M_0), peak particle velocity parameter PPV_W and continuous passive tomographic imaging.

Another important problem is related to the time changes of seismic hazard zones during the mining process, because it is necessary to consider not only spatial location of these zones, but also their time changes. In order to achieve this goal analysis of the abovementioned seismic parameters in moving time windows is proposed. This approach enables improvement in preparation and application of seismic hazard prevention activities. As confirmed by mining practice, adjustment of coal face speed in longwall mining system to mining-geological situation and assessment of potential seismic hazards (Drzewiecki & Makówka, 2013), with proper selection of active prevention – in the form of distress blasting, hydraulic fracturing etc. – allows to increase the effectiveness of tremor prevention activities and reduces this risk. Due to this the safety of miners in areas of rock burst hazard increases. The possibility of daily assessment of seismic and rock burst hazard and consequently the ability to conduct rational preventive actions was not provided before in Polish coal mines.

It should be pointed out that in recent years continuous seismic and rock burst hazard assessment is performed with the use of passive tomographic imaging (Lurka, 2009). An increasing number of seismic events recorded by modern seismological systems, e.g. Seismic Observation System – GIG, make it possible to efficiently utilize passive tomography method to determine seismic velocity images in consecutive short time periods i.e. every few days or even on daily basis. The ability to obtain tomographic velocity images every few days allows for quick application of preventive actions and reduce more effectively seismic and rock burst hazard. The seismic velocity anomalies on tomographic images indicate areas where the active prevention is required.

The effectiveness of presented seismic criteria to assess seismic and rock burst hazard, which are based on the sequential analysis of seismic parameters in daily moving time windows, was shown in figures 1-3 for coal panels 3/503 and 6/510 in Bobrek mine. More detailed information of these criteria are also presented in literature (Dubiński & Mutke, 2012; Mutke & Pierzyna, 2010; Lurka, 2009; Pierzyna, 2014). Mutke & Pierzyna (2010), present an assessment of seismic hazard in the coal panel no 3/ 503, where time changes of the ***b*** value of Gutenberg-Richter law in daily moving time windows in the period of 20-days were shown. Seven strong seismic tremors with seismic energies between $5 \cdot 10^6$J and $8 \cdot 10^8$J occurred during the operation of coal panel 3/503. The ***b*** parameter reached value from 0.55 to 0.9 whiles the occurrence of these strong seismic events. The values of ***b***-value parameter for all high energetic seismic tremors were much lower than the average value equal to 1.34. The average value of ***b***-value parameter was calculated for seismic events that occurred in the period of 23 years in the Bobrek mine (Pierzyna, 2014). The values of the ***b***-value during the occurrence of strong seismic tremors were also lower than the average values of the ***b***-value assumed usually to be equal to 1 in global seismology. It can be shown that anomaly $A_{G\text{-}R}$ of ***b***-value calculated in Bobrek mine just before the occurrence of seven strongest seismic tremors varied from 59% to 33%, which indicates, using the new seismic criteria, that seismic hazard level was in **c** or **d** level (medium or high, see table 2). This confirms high usefulness of the new seismic criteria, determined on the basis of seismological digital recordings. It should be noted that in case of the analyzed mining process, the strongest seismic tremors caused no damage on mine workings due to the distant location of its hypocenters (at least 500 m below the level of current mining). These tremors did not caused sufficiently strong vibration in the vicinity of mine workings which could produce rock burst phenomenon (Dubiński & Mutke, 1996). The results of continuous measurement of weighted peak particle velocity parameter PPV_W confirmed also that for the strongest tremors the recorded *PPV* values did not exceed 0.05 m/s. The recorded *PPV* values indicated that these strong tremors were located at large depths, deeper than the current mining level. More detailed analysis of *PPV* values in Bobrek mine was shown in article written by Marcak & Mutke (2013).

One can conclude that using time sequence analysis of seismic parameters allows for better assessment of seismic and rock burst hazard in mines.

6. Conclusions

The new criteria of seismic and rock burst hazard assessment in mines with longwall mining system were presented. These criteria utilize most of the routinely used seismic parameters i.e. seismic energy, seismic energy release per unit coal face advance, location of seismic events, ***b***-value of Gutenberg-Richter law, seismic energy index *EI*, seismic moment M_0, weighted value of peak particle velocity PPV_W and tomographic velocity values. The new feature is the development of quantitative criteria of seismic and rock burst hazard assessment that is based on continuous seismic data acquisition and time series analysis of the seismic parameters in moving time windows.

The presented results confirm that seismic and rock burst hazard assessment utilizing time series analysis of selected seismic parameters is essential to successfully monitor rock mass state in mines. If one only uses one seismic parameter only then seismic hazard assessment based on it would be of poor quality and could lead to false conclusions. All calculated values of seismic parameters were used to develop quantified criteria of seismic and rock burst hazard assessment with four-level scale.

An important aspect of seismic and rock burst hazard assessment is the problem of time changes of the areas with high stress state during mining process. Therefore not only a location of potential seismic hazard zones, but also their time changes in daily moving time windows and daily reporting system were proposed.

The new criteria of seismic and rock burst hazard assessment enable significant improvement in preventive actions and increase work safety in underground mines.

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