b-value as a criterion for the evaluation of rockburst hazard in coal mines

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ABSTRACT
Every year, a few rockbursts with fatalities and several hundred meters of damaged excavations have occurred in the mines of the Upper Silesia Coal Basin (USCB) in Poland. This paper presents a method for assessing the levels of seismic and rockburst hazards, using continuous seismological observation in the Bobrek coal mine. This assessment is based on the study of the Gutenberg-Richter (G-R) relation for current and past mining in the coal field. According to many laboratory and field studies, the *b*-value may be an indicator of fluctuations in stress levels (Scholz, 1968; Gibowicz, 1974; 1979), and the consequent seismic hazard.

The novelty of the presented research is the development of a quantitative criterion based on *b*-value changes, calculated in moving time windows with a 1-day step, and the anomalies resulting from the comparisons of the temporal values of *b* with its average value for the past seismicity in the field of coal mining; $A_{G-R} = [(b_m - b)/b_m] \cdot 100\%$ (where b_m is the average value of *b* for the field of coal mining and b is the temporal value of coefficient *b*, calculated in time windows). This approach allows us to standardize the criterion to the current values of *b* in the investigated area (Table 1). In many measurement examples, high values of the temporal anomaly A_{G-R} and at the same time downwardly trending and low *b*-values before the occurrence of strong mining seismic events were documented in this paper and in studies by Pierzyna (2014). Particularly interesting results were obtained from mining and geological conditions that led to the formation of local zones of stress concentration (Dubiński, 1989), and increases in seismic activity and seismic hazard.

The *b*-value criterion is in agreement with the four basic levels of rockburst hazard used in Polish coal mines (Mutke et al., 2015).

KEYWORDS: Mining induced seismicity; *b*-value; seismic criterion

1. INTRODUCTION

The Gutenberg-Richter Law (G-R) is the most common model of a relation between the magnitude and number of seismic events (Gutenberg and Richter, 1954; Utsu, 1999). It is well documented in global earthquake seismology. Weak tremors are much more common than strong ones, and the frequency-magnitude relation takes on a logarithmic scale of the form $\log N(M) = a - b \cdot M$, where N is the number of seismic events with magnitude equal to or larger than magnitude M, M is the magnitude and *a* and *b* are coefficients related to seismicity.

The coefficient *b* in this law is used globally in statistical seismology to characterize and compare the levels of seismic activity in different areas of the earth's crust (Utsu, 1999; Shearer, 2009). This factor varies over time on regional or local scales (Gibowicz, 1974; 1979), and it reflects the change in the level of stress around the average value. Specifically, the *b*-value decreases prior to the occurrence of strong earthquakes (high state of stress) and increases after its occurrence (lower stress level after relaxation).

Relatively few uses of this factor to characterize the level of seismic and rockburst hazard in underground coal mines can be found in the literature (Lasocki, 1990; Holub, 1995; Fritschen, 2009; Mutke and Pierzyna, 2010; Pierzyna, 2014). The frequency-magnitude law works even down to magnitude -4.4 in deep mining (Kwiatek et al., 2011). Low *b*-values imply that strong mining seismic events prevailed in the studied set. In an assessment of rockburst hazard in Poland, strong mining tremors located close to the excavations and high stress level played fundamental roles (Mutke et al., 2015).

2. METHODOLOGY

In this work, a systematic analysis of the *b*-value and anomaly of the *b*-value, determined in time windows, was correlated with observed seismicity in time and with the geological and mining conditions.

To calculate the *b*-value in the G-R Law, applying the method of maximum likelihood has been proposed (Aki, 1965; Utsu, 1965; 1999; Marzocchi and Sandri, 2003):

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$$b = (\log e) / (M_a - M_{min})$$

where e is the base of natural logarithm, M_a is the sampling average of the magnitudes, and M_{min} is the threshold of magnitude completeness.

The evaluation of its standard deviation in this study was based on the formula derived by Shi and Bolt (1982).

It should be emphasized that to calculate the *b*-value, the selection of a set of tremors is made in accordance with the principle of catalog completeness. It is identified on the basis of cumulative quantity histograms at magnitude intervals and also on the basis of the technical threshold of the seismological network capabilities in recording all seismic events.

The ongoing assessment of seismic hazard in LP No. 3/503 (backward analysis) was made by analyzing variations of the *b*-value, calculated in time windows with a moving 1-day step. A 20-day window was selected as optimal for the technological process (based on stationarity of the seismic process in mines (Lasocki, 1990), and the number of seismic events in a window of time (more than 30)). The useful quantitative category classifications for seismic and rockburst hazard levels provide an anomaly of the *b*-value, defined as follows:

$$A_{G-R} = [(b_m - b)/b_m] \cdot 100\%$$

where b is the temporal coefficient value, calculated in time windows, and b_m is the average value of *b*, determined for the entire catalog of seismic events previously recorded in the field panel of coal mining.

A high anomaly of the *b*-value should correlate with the preparation of the rock mass for the occurrence of strong mining related seismic events.

3. MONITORING SEISMICITY IN PANEL 3/503 AT THE BOBREK MINE

The field measurements and study of the *b*-value were performed in the Bobrek Mine, one of the deep coal mines in USCB, Poland. The database used for *back analysis* in the Bobrek Mine included seismic data as well as geological, mining, and technological data for 5 longwall panels (LP). Studies of the *b*-value were conducted for the seismicity during extraction of the 503 coal seam by LP No. 2 and No. 3, of the 509 coal seam by LP No. 91a and No. 92a, and of the 510 coal seam by LP No. 6 (Mutke and Pierzyna, 2010; Pierzyna, 2014). In this paper, we show a study of LP 3/503 in detail, mined from April 2009 to June 2010. Coal seam 503 was 3.0 m thick, the excavation face was approximately 350 m, and

the longwall panel was approximately 1000 m long, located 700 m below the ground surface. In total, (1) 2996 seismic events were recorded with magnitudes ranging from $M_L =0.1$ to $M_L =3.8$ (M_L – local magnitude calculated using the empirical formula developed for Upper Silesia between seismic energy and magnitude calculated from the body wave: $\log E = 1.8 + 1.9 \cdot M_L$; (Dubiński and Wierzchowska, 1973)) The hypocenters of the strongest seismic events were located 300-800 m deeper than the level of the 503 coal seam (Marcak and Mutke, 2013).

Seismic monitoring in the "Bobrek-Centrum" mine was performed with a 64-channel underground seismic network (Seismological Observation System (SOS) designed by the Central Mining Institute in Katowice, Poland) consisting of 1 Hz velocity DLM2001 and DLM3D type probes. SEISGRAM and MULTILOK software were used to process and analyze the seismic data. Seismic stations were deployed underground as shown in Figure 1. The locations of the 2,996 seismic events are also shown in Figure 1.

A method for evaluating the completeness of seismic events during extraction of LP No. 3/503, due to technical reasons, involves an assumption that all seismic events will be triggered when the signal on the nearest five sensors exceeds the seismic noise level by two times. In the case of the LP No. 3/503 contour, the most distant of the five seismic sensors is located at a distance of 700 m. In such conditions, (2) it is possible to obtain *catalog completeness* of mining tremors of local magnitude $M_L=0.6$ and higher. For the whole area of the Bobrek Mine, the seismic *catalog completeness* begins from magnitude $M_L=0.9$.
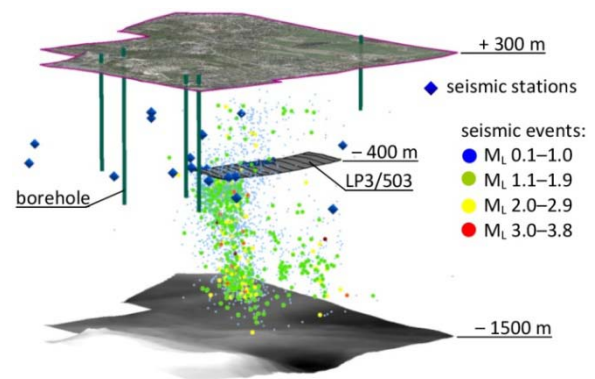

Figure 1: Bobrek Mine field site – deployment of seismic sensors around LP 3/503 (blue diamonds) and location of the mining tremors hypocenters (circles). Color of the circle indicates the size of the magnitude.

4. GUTENBERG-RICHTER RELATIONS FOR THE BOBREK MINE

4.1 The mean b-value for seismicity induced by mining in the Bobrek Mine in the years 1990-2013

The calculation of the frequency-magnitude relation at the Bobrek Mine was made for the seismic events of magnitude $M_L \geq 0.9$ recorded during the 1990-2013 years. The seismic catalog included 15700 seismic events.

The results of the GR distribution for the Bobrek Mine are illustrated in Figure 2. It is apparent that, for the higher magnitudes, i.e., in the range of 2-3.8, a slight downward deviation of the empirical values occurs from the theoretical straight line of the Gutenberg-Richter law. The average **b**-value amounted to $b_m=1.34$ for the 23-year period of mining and will be used as a reference for further calculation of rockburst hazard in the Bobrek Mine.
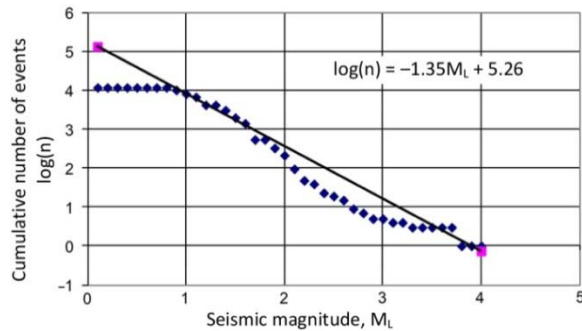

Figure 2: The cumulative distribution of seismic events above magnitude $M_L=0.9$ registered in the Bobrek Mine in the 1990-2013 years.

4.2 The changes in the b-value and anomaly of the b-value during the extraction of coal in panel No. 3/503

The mining in LP No. 3/503 induced very high seismicity with magnitudes higher than $M_L=3.5$. The coefficient of **b** for this seismicity reached a value of 0.99 and was 27% lower than the **b**-value obtained for mining in the whole area of the Bobrek Mine in the 1990-2013 years. This means that the mining in LP No. 3/503 took place under potentially higher seismic hazard than past mining in the Bobrek Mine. The main reasons for the high level of seismic hazard in LP No. 3/503 are due to mining in the axis of Bytom through the zone where there is high tectonic stress and in the local zones of stress concentration resulting from past mining conditions (remnants, edges).

The ongoing assessment of the seismic hazard level in LP No. 3/503 was made by analyzing fluctuations of the **b**-value calculated in 1-day time windows. The 1-day moving variations of the **b**-value

and 6 strongest tremors during the extraction of coal in LP No. 3/510 are plotted in Figure 3. The occurrence dates of these strong seismic events are indicated by arrows. The values of the *b* coefficient during the strongest seismic events ranged from 0.55 up to 0.9 and were much lower than the average value of $b_m=1.35$ calculated for seismicity in the Bobrek Mine.
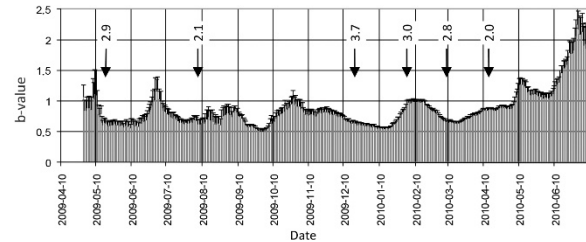

Figure 3: The changes in the **b**-value of the Gutenberg-Richter law, calculated in a time window of 20 days with a 1-day moving step in LP No. 3/503 during the period of April 2009 – June 2010. The darker lines represent the error bars calculated for every window's data using the equation derived by Shi and Bolt (1982). The strongest tremor of magnitude $M_L=3.7$ occurred on 16.12.2009 while the coefficient of *b* reached the lowest level.

They were also lower than the global average values of the **b** factor for seismicity, adopted in the literature as 1.0 for the world (Shearer, 2009). By referring these values to b_m, it can be found that the seismic anomaly ranged from 59% to 33%. The study of LP 3/503 clearly indicates that strong mining induced seismic events occurred when the observed **b**-value level was low and the anomaly of **b** was very high.

Particularly interesting results were obtained by Dubiński (1989) for representative mining and geological situations that led to the formation of local zones of stress concentration and, as a consequence, an increase in seismic activity and seismic hazard. In Figure 4, an example of mining conditions' influence on the distribution of the **b**-value is shown. The **b**-values were calculated in moving windows of time during the passage of LP No. 3/503 in the zone of impact of the 501 coal seam edge, located 27 meters higher. Lower values of **b** were obtained when the extracted face of LP No. 3/503 was on the unmined side of coal seam 501. During this time, the seismic activities increased significantly. The GR seismic anomaly reached a very high value, $A_{G-R} = 59\%$.
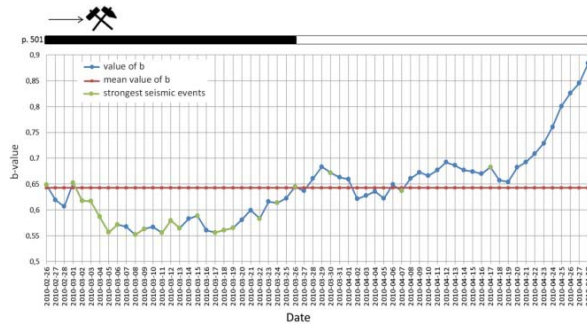
Figure 4: The distribution of the *b*-values obtained during the passage of the LP 3 coal face under the edge of the 501 coal seam.

5. CRITERION OF ROCKBURST HAZARD IN THE BOBREK MINE

The novelty of the results of the research presented lies in the development of quantitative criteria based on the analysis of the G-R distribution in a moving time window with a 1-day step, taking into account the anomalies of the *b*-value. This approach allows us to standardize criterial values to the temporal value of *b* calculated in time windows. In many examples described in the paper, high values of the anomaly of coefficient *b* and downwardly trending low *b*-values were documented before the occurrence of the strongest tremors. The *b*-value criterion corresponds to the four levels of rockburst hazard used in Polish mines (Table 1). In cases when the *b*-value criterion is used, it is easier to select and monitor the effectiveness of prevention activities. The primary prevention activities are based on the performance of blasting and rock fracturing ahead of the LP face line to induce stress relaxation in the area of mining. Another preventive action was the selection of appropriate support in the zones with high seismic hazards.

Table 1: *b*-value empirical criterion of rockburst hazard in the Bobrek coal mine.

Level of rockburst hazard	Anomaly of *b*-value, %	*b*-value condition
lack	$A_{G-R} < 0$	$b > b_m$
low	$25 > A_{G-R} \geq 0$	$b \leq b_m$
medium	$50 > A_{G-R} \geq 25$	$b < b_m$
high	$A_{G-R} \geq 50$	$b < b_m$

6. DISCUSSION

The results indicate the usefulness of *b*-value changes in moving time windows and the anomaly coefficient of *b* for evaluating the preparation of rock mass to induce strong seismic events in the Bobrek Mine.

As a result of the work described in this article, calculations were presented that led to the formulation of a local criterion for the ongoing assessment of seismic and rockburst hazards in the Bobrek Mine. This quantitative criterion, using the *b*-value and anomaly of *b* calculated in moving time windows, is novel in the field of the assessment of seismic and rockburst hazards in deep coal mines.

Documenting and analyzing the results of observations under the geological and mining conditions that cause stress concentration are especially important from the point of view of safe mining. This study presents the results of calculated distributions of *b*-values and anomaly of *b* for the following typical and frequently encountered mining situations and geological conditions:

− mining within the impact of coal seam edges,
− mining within the influence of remnants,
− mining within the influence of the fault,
− mining within the influence of tectonic stresses throughout.

Good results can be obtained when several indicators are used to assess the seismic hazard level (Mutke et al., 2015).

7. CONCLUSIONS

The use of the G-R law provides a reliable evaluation of potential areas of high seismicity in underground coal mining. The assessment is performed on the basis of estimating the *b*-value and its distribution for the current mining extent, using 1-day moving time windows.

Seismicity in mines primarily depends on the geological and mining conditions under which the operation is conducted. Studies have shown effective efforts to link changes of the *b*-value with various geological and mining conditions prone to stress concentration (e.g., edges of old exploitations, remnants, faults or other geological structures).

The novel result of this research lies in the development of a quantitative criterion of rockburst hazard assessment in the Bobrek Mine, elaborated on the basis of the *b*-value and on the anomaly of the *b*-value.

High anomalies of the *b*, the low value of *b* and a downward trend in *b* were documented before high seismic activity and the strongest seismic events. The *b*-value criterion was developed in accordance with the "complex criterion", which corresponds to the four levels of rockburst hazard assessment and is one of several seismological criteria used in Polish mines. The diverse mechanisms of seismic events in deep mining require the use of various seismic indicators.

The method presented in this paper can be used to assess seismic hazard in deep mines after

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verification of the quantitative level of the **b**-value criterion. This should be done through analysis of former seismic data due to the variety of geological and mining conditions, i.e., *back analysis*. It should lead to improvement in the effectiveness of rockburst prevention and increases in the safety of the miners.

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