Study on energy distributions of strong seismic events in the USCB

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Abstract

The paper presents the statistical analysis of energy distribution of strong seismic shocks (energy $E \geq 10^5$ J) occurred in the Upper Silesian Coal Basin which is one of the most seismically active mining areas in the world. In the USCB tremor epicenters do not occur uniformly throughout the whole basin but group in several regions belonging to different structural units and are separated by regions where strong shocks are not observed. The aim of the studies was to determine the modality of the energy distributions and to compare the modal types in regions of the USCB where the shocks epicenters cluster. An analysis was made for shocks with energies equal to or greater than 10^5 J recorded by Upper Silesian Regional Seismological Network operated by Central Mining Institute (CMI), which took place between 1987 – 2012. The analysis has proven the bimodality of seismic energy distribution in the three of five studied areas of the Upper Silesian Coal Basin. The Gumbel's distribution II type best fit the experimental energy distribution for almost all studied tectonic units except the main syncline area, where the Gumbel's distribution I type matched better the low-energy mode. This is due to too short time window, causing a shortage of the strongest shocks in seismic catalogue.

Key words: induced seismicity, mining tremors, energy distribution, bimodality of the energy distribution, Gumbel's distribution

Introduction

Upper Silesian Coal Basin (USCB) in Poland is one of the most seismically active mining areas in the world. In the USCB tremor epicenters do not occur uniformly throughout the whole basin but grouped in several regions belonging to different structural units and are separated by regions where strong shocks are not observed (Fig.1).

Former research of seismicity in the Upper Silesian Coal Basin showed that it has a bimodal character (Kijko 1986). Tremors occurring in the USCB can be divided into low-energy events caused directly by the underground exploitation and regional ones (high-energetic), the cause of which are not yet fully explained (Pilecka & Stec 2006).

The first type of seismic activity directly related to mining activities is present in the neighborhood of active mine workings. These weaker phenomena are characterized by the type of the explosive mechanism in tremor sources, which reflects the processes related to the destruction of the excavation or rocks in its direct surroundings (Stec 2002).

The second type of seismicity is probably induced by the combination of two factors: the mining and tectonic one. These high-energy shocks occurred in areas of tectonic zones and frequently are felt in the surface. The cause of the strongest tremors can be cumulation of exploitation and tectonic stresses acting in the same parts of the rock mass (Stec 2007).

One should pay special attention to the fact that epicenters of strongest mining tremors

group mostly in regions where the underground exploitation is carried out in the vicinity of major fault zones. Until now conducted researches for the spatial distribution of strong seismic events showed that epicenters of consecutive shocks shows directional compatibility with one of the dominant fault trends in particular structural unit (Idziak, et. al., 1999). Jura in his research (1999) showed that the Kłodnica fault zone (the main syncline) can be considered as a modern seismogenic structure. The Young-Alpine tectonic stresses, which have a significant impact on the nature of mining-induced tremors, may appear in the northern part of the Kłodnica fault. This phenomenon may indicate on natural relaxation of remnant tectonic stresses accumulated in this area.

According to Kijko (1986) the bimodality of the energy distributions has its origin in different physical processes that take place in the tremor's hypocentre – in this case different "mechanisms for generating shocks" are mentioned.

Gibowicz (1989) suggested that bimodality of the seismic energy distributions is the result of inhomogeneity and discontinuity of the rock mass and all shocks are involved by a stress induced by mining works. The low-energy seismic mode is the result of stress discharging caused directly by mining, and the high-energy mode is the result of synergies between exploitation and tectonic activity in the given area.

The article presents results of studies on statistical analysis of cumulative energy distribution of seismic events recorded by Upper Silesian Regional Seismological Network operated by Central Mining Institute (CMI). The seismic database contains events of energy greater than or equal to 10^5 J recorded during the period 1987 – 2012 in different regions of the USCB: the main syncline area, the main anticline area, the Rybnik Coal District, the Kazimierz syncline area and the Bytom syncline area.

Upper Silesian Regional Seismological Network operated by Central Mining Institute (CMI) enables registration of seismic energy greater than or equal to 10^5 J (local magnitude M_L 1,6). The network operates in a system of continuous monitoring and detection of vibration which is done automatically. Seismic signals are received by 20 measuring channels located throughout the monitored area. In the years 1987 – 2012, 26 085 tremors of energy greater than or equal to 10^5 J (M_L 1,6) from the USCB were documented (Fig.2).

**Energy distributions of strong seismic events**

In seismology the Gutenberg–Richter (G-R) law is used to determine the distribution of the number of shocks as a function of magnitude. G-R law expresses the relationship between the magnitude (M_L) and total number of earthquakes (n) in any given region and time period of at least that magnitude (Gibowicz, Kijko, 1994):

$$\log n = a - b\, M_L, \tag{1}$$

where:
n – is the number or the cumulative number of shocks having magnitude $\geq$ M, a, b – are coefficients (Idziak et al., 1999).

G-R law is an important equation describing the seismic energy release. Coefficient 'a' is a measure of the seismic activity of the area, whereas the coefficient 'b' characterizes the way of accumulated strain energy release. The parameter b is commonly close to 1.0 in seismically active regions. Its high values (greater than 1) mean that the seismic energy is released mostly in a plurality of low energy shocks. On the other hand the low values of parameter b (less than 1) mean the presence of an increased number of higher energy shocks in the G – R distribution (Idziak et al., 1999).
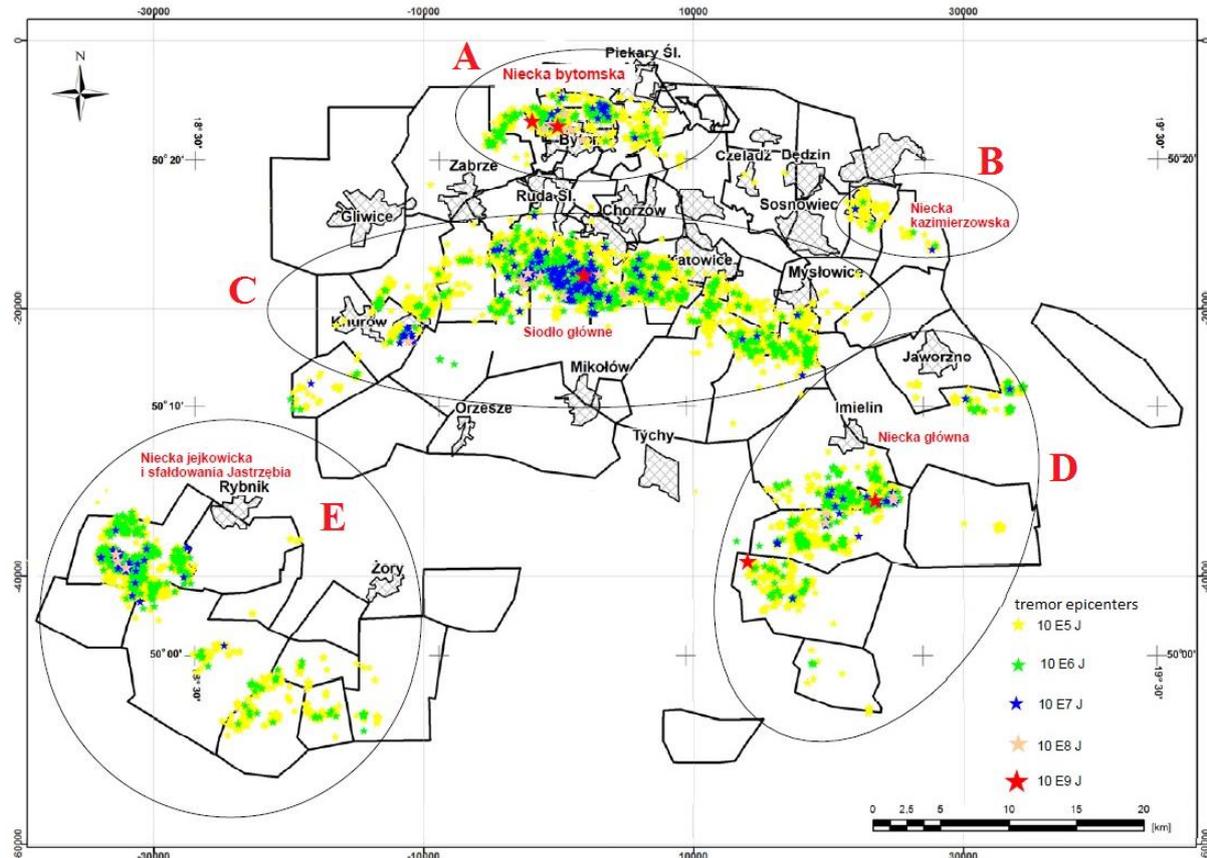
Fig.1. Localizations of strong seismic phenomena (energy $E \geq 10^5$ J) in the Upper Silesian Coal Basin from the years 1987-2012 on background of mining areas (after Stec, Lurka, 2013, modified) A – the Bytom syncline area, B – the Kazimierz syncline area, C – the main anticline area, D – the main syncline area, E – the Jejkowice syncline and Jastrzębie fold zone (Rybnik Coal District)
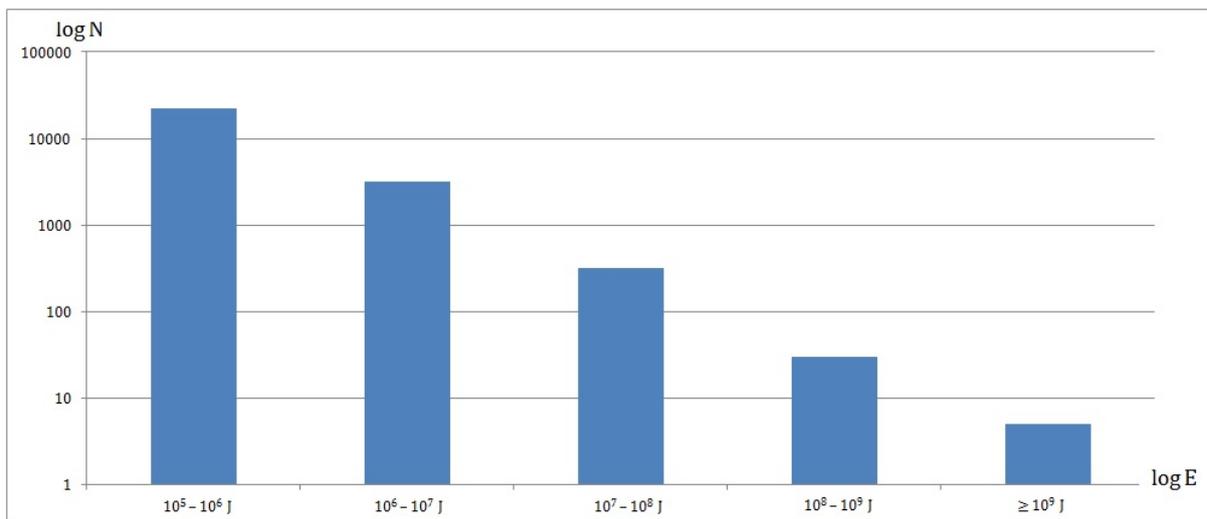
Fig.2. Histogram presenting logarithmic number of tremors for energy intervals $10^5 - 10^6$ J (22607 tremors), $10^6 - 10^7$ J (3160 tremors), $10^7 - 10^8$ J (321 tremors), $10^8 - 10^9$ J (30 tremors), $E \geq 10^9$ J (5 tremors) for the whole USCB. N – number of events, E - energy

The results obtained for investigated areas basing on the Central Mining Institute (CMI) seismic catalog from the years 1987 – 2012 appointed that estimated spatially and temporally averaged coefficient b was equal to 1.82 (Fig.3), what indicating that in the USCB seismic energy is released rather by a small events than by large ones.

In order to investigate the energy distribution the empirical cumulative distribution functions (ECD) were calculated according to the formula (Idziak et al., 1991):

$$F (x) = P (x \leq E) = \frac{ni}{N+1} \tag{2}$$

where:

n_i –number of events with energy less than or equal to the E, N – total number of events in selected time period.

The empirical cumulative distribution (ECD) can be approximated with Gumbel's extreme distribution (Gumbel, 1958) for which the equation describing probability is as follows:

$$F (E) = e^{-e^{-y(E)}} \tag{3}$$

where:

F(E) – the cumulative distribution function (CDF), E – shock energy,

Based on Jenkinson's method, three types of Gumbel's distribution can be used. First asymptotic distribution (I type) can be presented in the form of:

$$y (E) = K \cdot (E - v) \tag{4}$$

where:
K – distribution parameter, v – value of energy, for which y = 0.

If we specify the dependence between E = f(y), then first asymptotic distribution (I type) determines the linear relationship between E and y which is unlimited both for lower and upper sides of the distribution. It means that the both - very strong and very weak shocks can be observed.

Second asymptotic distribution (II type) one can however present in the form of:

$$y (E) = \ln \left(\frac{E - \varepsilon}{v - \varepsilon} \right)^K \tag{5}$$

where:
K – distribution parameter, E – shock energy, v – value of energy, for which y = 0, ε − a lower cut in Gumbel's distribution type II.
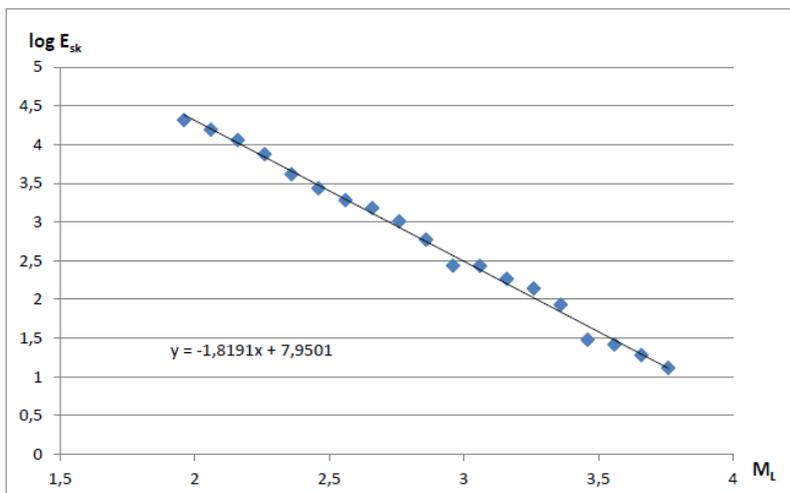
Fig.3. Spatially and temporally averaged coefficient b ~ 1,82 estimated for the whole USCB (from the years 1987 – 2012). **Esk** – cumulated energy, **M_L** – local magnitude

For second type of Gumbel's distribution function E(y) is defined for shock energy equal to or bigger than the certain threshold energy ε and is convex downward.

Third asymptotic distribution (III type) in turn, has the form:

$$y\ (E)\ = \ln\ (\frac{\omega - E}{\omega - v})^K \qquad (6)$$

where:
K – distribution parameter, E – shock energy, v – value of energy, for which y = 0, ω – an upper cut in Gumbel's distribution type III.

Third type of Gumbel's distribution is not defined for certain upper limit of energy and E(Y) is a function of a convex upward. This means that the dataset may not contain shocks of energy higher than ω.

In order to fit the experimental cumulative distribution function (ECD) for the different areas of the USCB by an appropriate Gumbel's distribution, the seismic data catalog of the Central Mining Institute (CMI) from the years 1987 – 2012 was used to calculated empirical value of the function y (E) as:

$$y\ (E) = -\ln\ (-\ln\ (F)) \qquad (7)$$

where:
F(E) – the experimental cumulative distribution function (ECD).

Results of statistical analysis of energy distribution

Gumbel's distributions of I, II and III type were tested to prove which of them best estimate the ECD's obtained for designated epicenters clusters.

Curvilinear regression module of *Statistica* computer program was applied for the purposes. For each separated ECD Gumbel's distributions of a specific type, which was characterized by the smallest merit function

and the largest curvilinear correlation coefficient was selected. The values of these parameters are shown in the table 1.

Analysis included shocks with energy equal to or greater than 10^5 J which generally could belong to low-energy mode but some of them could belong to high-energy mode. The modes separation was based on occurrence of characteristic inflection points on the graphs presenting ECD's. Precise separation of the shocks belonging to either one or the other mode on the basis of the energy data is not possible because distributions of low and high energy mode overlaps for events with energy near to 10^6 J.

In presented analysis theoretical distributions of low-energy mode was matched to ECD in terms of energy from $1 \cdot 10^5$ J to about $7 \cdot 10^5$ J whereas for high-energy mode in terms of energy higher than $1 \cdot 10^6$ J.

To separate low-energy mode precisely tremors of energy much less than $1 \cdot 10^5$ J (for example from $1 \cdot 10^2$ J) registered by seismic mining networks should be taken into account. However, then the analysis would be very local and would involve specific mines whereas the analysis was focused on the entire USCB area.

The results of study showed that energy distribution of shocks from different tectonical units of the USCB cannot be estimated by the same Gumbel's distributions.

On the graphs presenting ECD for the main syncline, the main anticline and the Bytom syncline regions (Fig.4, 9 and 10) inflection points which indicate the existence of two independent branches of the analyzed distributions can be clearly observed.

Main syncline area

Analyzing the graph plotted for the main syncline area (Fig.4) it can be seen clearly that the ECD compounds two modes, separated by a characteristic inflection points.
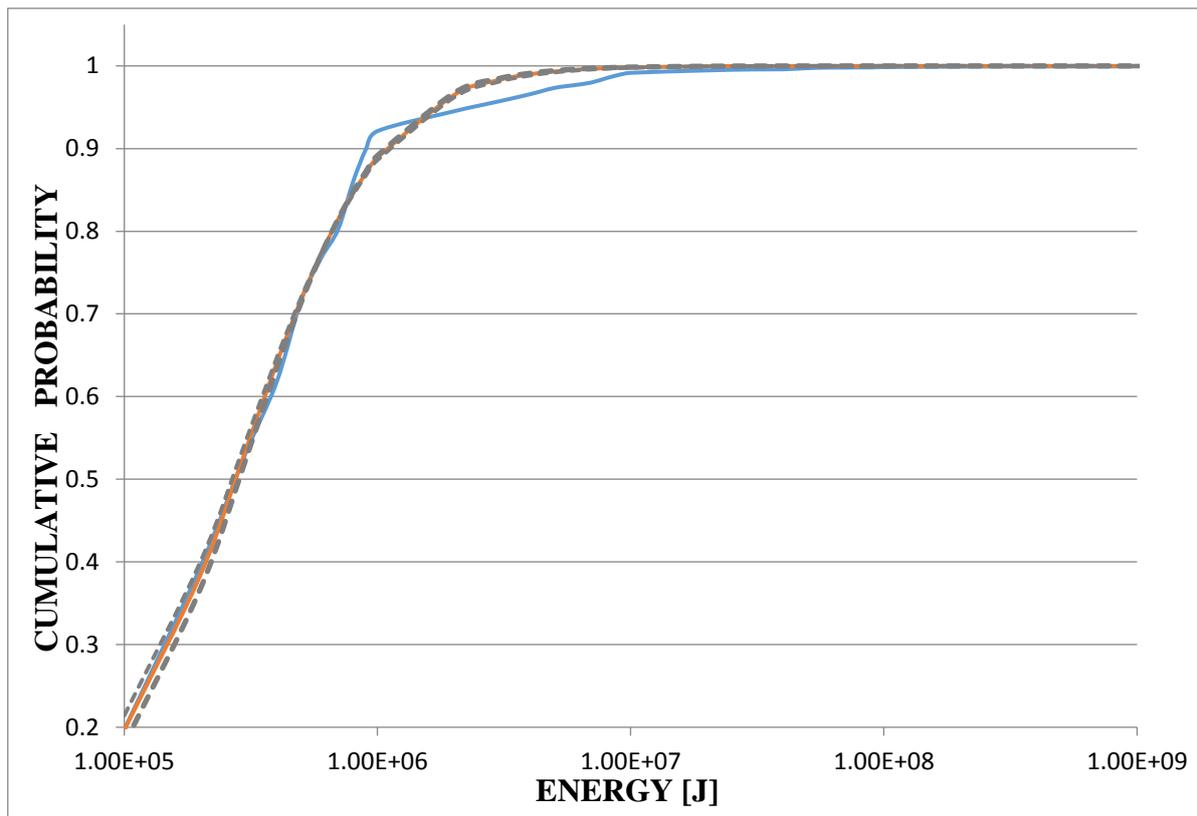
Fig.4. Seismic energy distribution curves from the main syncline region (1987 – 2012). Blue – empirical (ECD), red – theoretical (CDF), greys – 5% confidence intervals for CDF

Using curvilinear regression method, logarithmic function which corresponds to the Gumbel's distribution type II, best fit the high-energy branch ($7 \cdot 10^7$ J $\leq$ E $\leq 1 \cdot 10^9$ J) of the experimental distribution (Fig.6), whereas the Gumbel's distribution I type gave a better fit (Fig.5) for the low-energy mode ($1 \cdot 10^5$ J $\leq$ E $\leq 7 \cdot 10^5$ J).

Kazimierz syncline area

In the Kazimierz syncline area (Fig.7) selection of the type and distribution parameters of high-energy were difficult, due to the insufficient number of shocks in the field of higher energies. It was not possible to separate the modes, but for the energy interval of $1 \cdot 10^5$ J $\leq$ E $\leq 6 \cdot 10^7$ J ECD can be well described by Gumbel's distribution II type.

Rybnik Coal District

In the Jejkowice syncline and Jastrzębie fold zone (RCD) bimodality of the energy distribution was also not observed (Fig.8). For the energy interval of $1 \cdot 10^5$ J $\leq$ E $\leq 6 \cdot 10^8$ J the ECD was well fitted by Gumbel's distribution II type.

Main anticline area

In turn, in the main anticline area distribution bimodality was found (Fig.9), which was indicated by the characteristic inflection points sharing the different energy modes. A better fit for low-energy mode (energy of $1 \cdot 10^5$ J $\leq$ E $\leq 1 \cdot 10^7$ J) was given by the Gumbel's distribution II type (Fig.10). In addition, high-energy mode (energy of $1 \cdot 10^7$ J $\leq$ E $\leq 1 \cdot 10^9$ J) also can be described by another Gumbel's distribution II type (Fig.11).
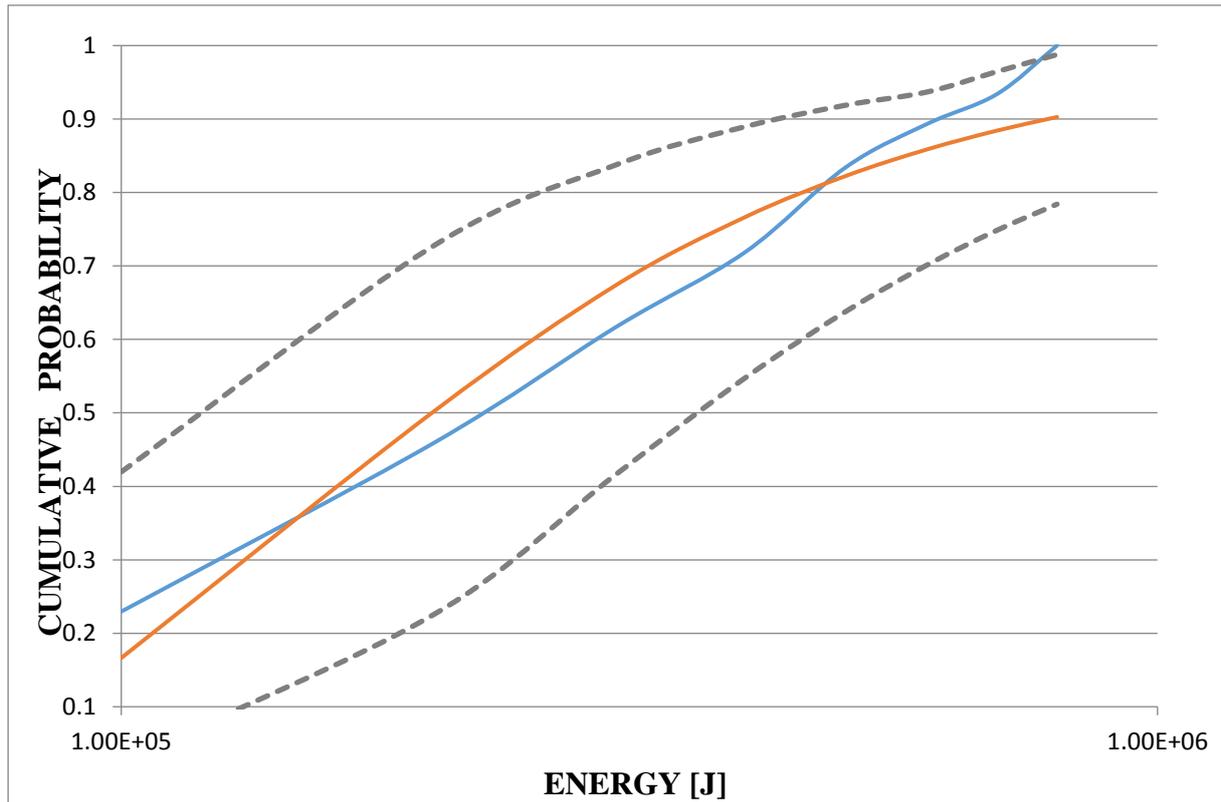
Fig.5. Seismic energy distribution curves for low-energy shocks from the main syncline region (1987 – 2012). Blue – empirical (ECD), red – theoretical (CDF), greys – 5% confidence intervals for CDF
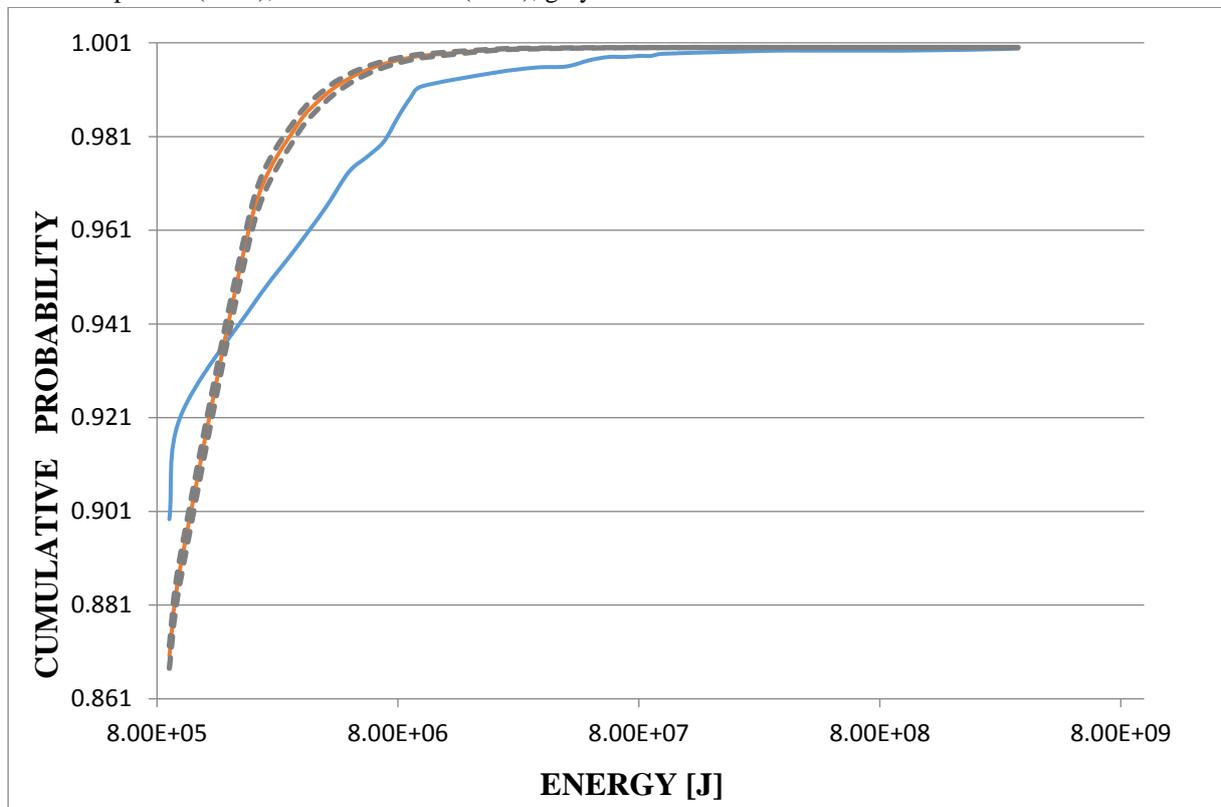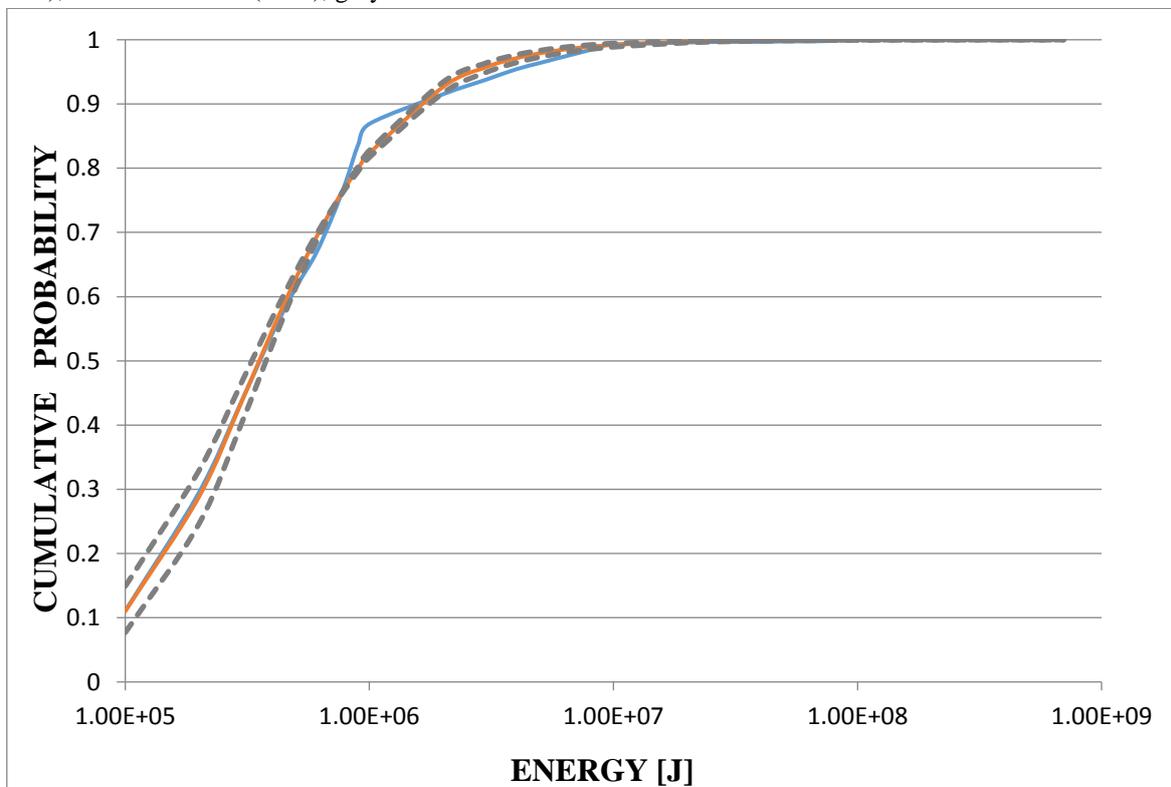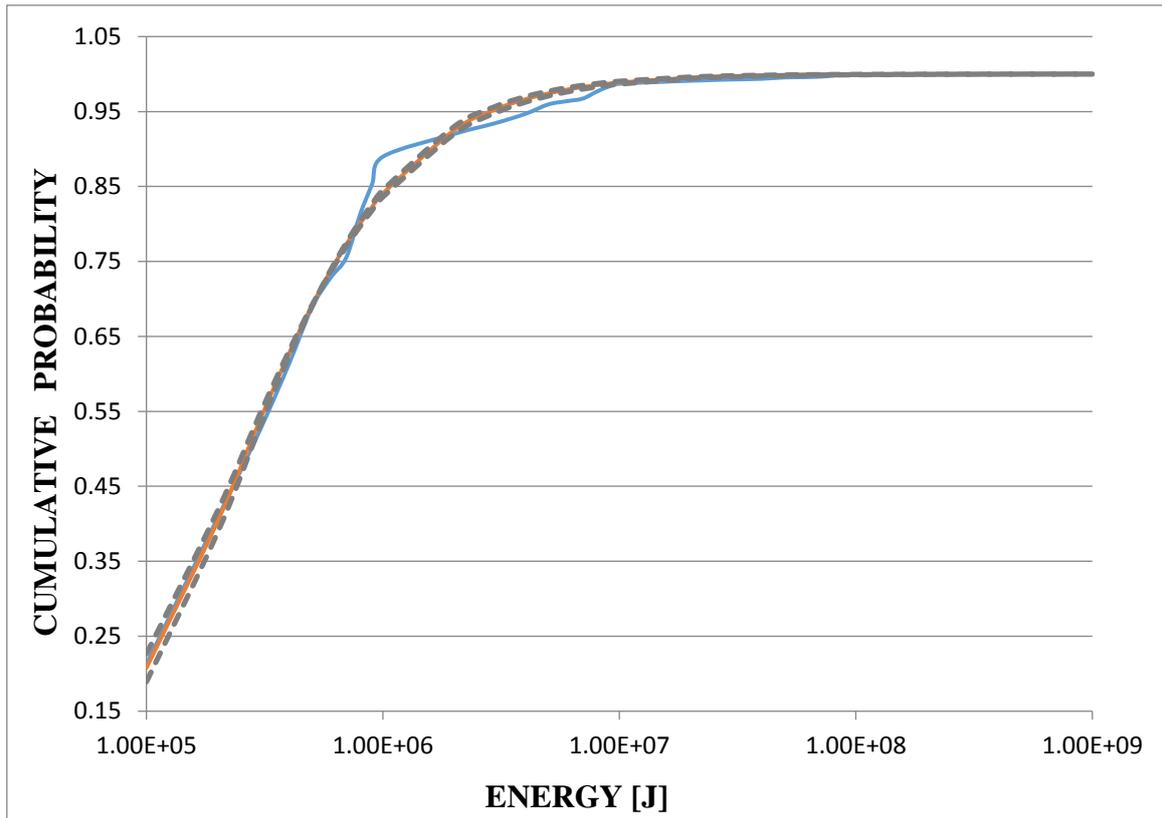

Fig.6. Seismic energy distribution curves for high-energy shocks from the main syncline region (1987 – 2012). Blue – empirical (ECD), red – theoretical (CDF), greys – 5% confidence intervals for CDF
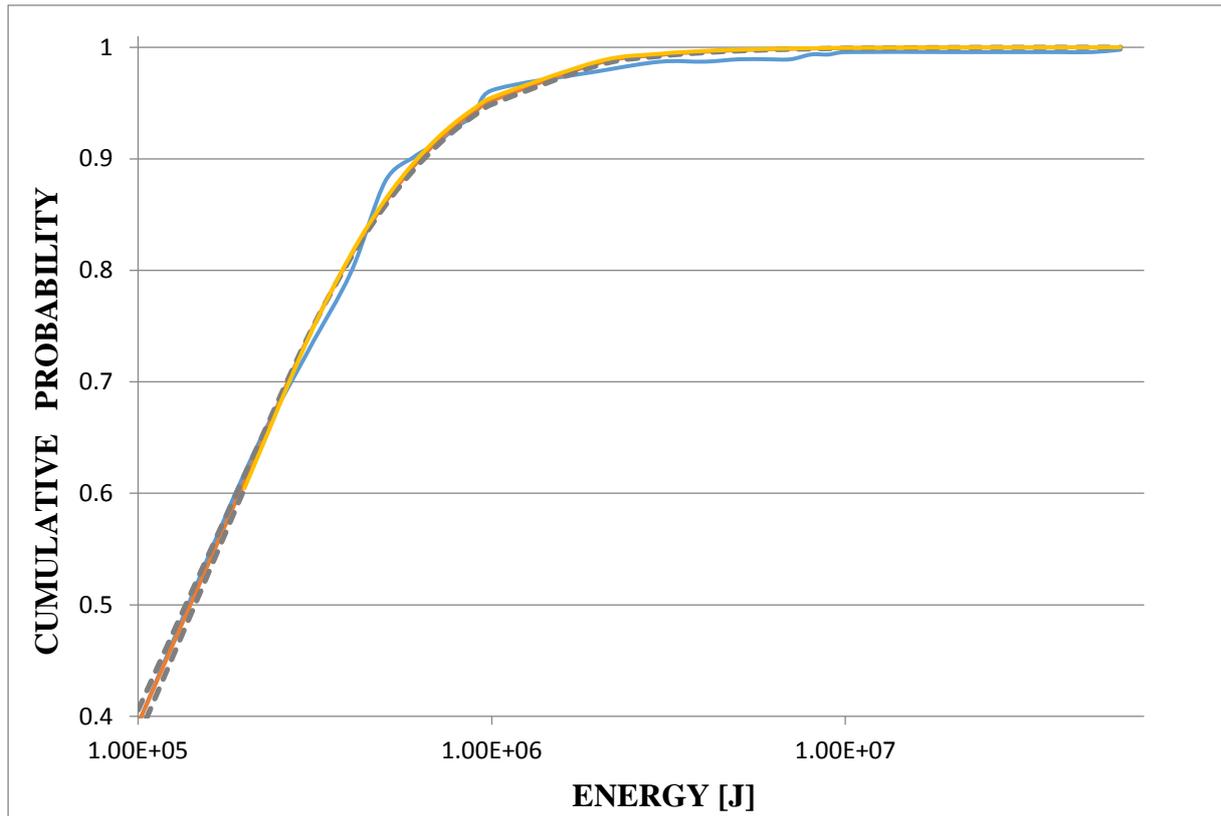
Fig.7. Seismic energy distribution curves from the Kazimierz syncline region (1987 – 2012). Blue – empirical (ECD), red – theoretical (CDF), greys – 5% confidence intervals for CDF

Fig.8. Seismic energy distribution curves from the Jejkowice syncline and Jastrzębie fold zone (Rybnik Coal District) (1987 – 2012). Blue – empirical (ECD), red – theoretical (CDF), greys – 5% confidence intervals for CDF

Fig.9. Seismic energy distribution curves from the main antycline region (1987 – 2012). Blue – empirical (ECD), red – theoretical (CDF), greys – 5% confidence intervals for CDF

Fig.10. Seismic energy distribution curves for low-energy shocks from the main antycline region (1987 – 2012). Blue – empirical (ECD), red – theoretical (CDF), greys – 5% confidence intervals for CDF
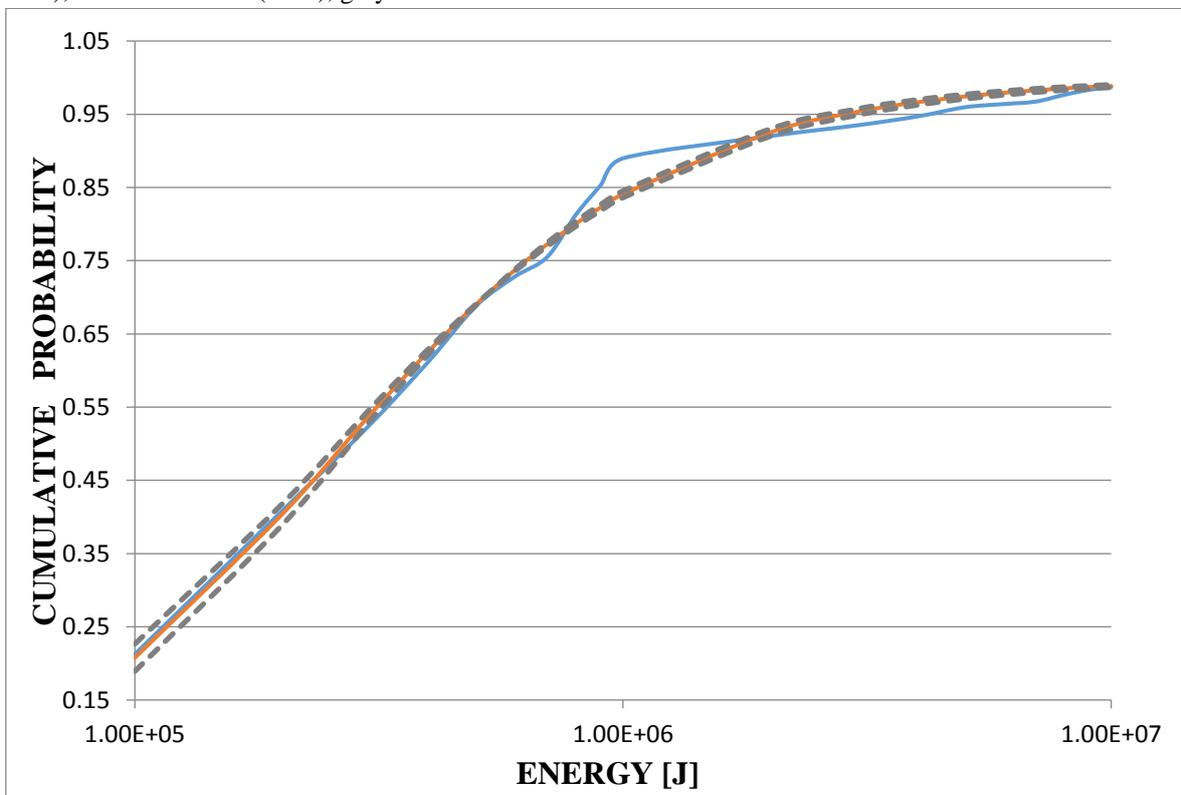
Fig.11. Seismic energy distribution curves for high-energy shocks from the main antycline region (1987 – 2012). Blue – empirical (ECD), red – theoretical (CDF), greys – 5% confidence intervals for CDF
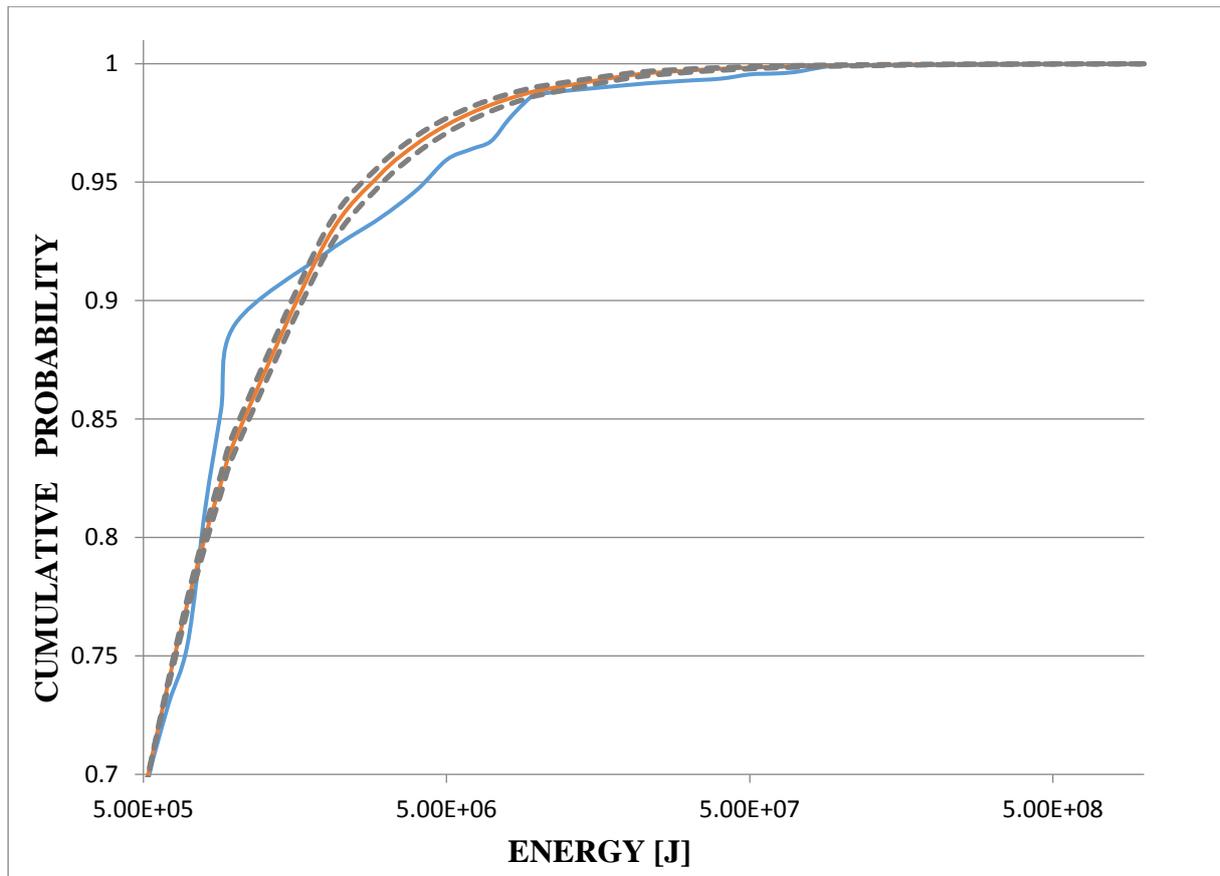
Bytom syncline area

The Bytom syncline area was also characterized by bimodal energy distribution (Fig.12). Both modes, low-energy (energy of $1 \cdot 10^5$ J $\leq$ E $\leq 5 \cdot 10^6$ J) and high-energy (energy of $1 \cdot 10^7$ J $\leq$ E $\leq 1 \cdot 10^9$ J) could be fitted by the different Gumbel's distribution II type (Figs 13 and 14).

Common results of the matching Gumbel's distributions and their statistical parameters (errors) for different regions of the Upper Silesian Coal Basin are presented in Tab.1.

Discussion and conclusions

The analysis carried out for the studied areas of Upper Silesian Coal Basin: the main syncline area, the main anticline area,

the Jejkowice syncline and Jastrzębie fold zone (Rybnik Coal District) the Kazimierz syncline area and the Bytom syncline area has shown that the greatest compatibility with experimental data of the energy distribution gave Gumbel's distribution II type, except the main syncline area, where a better matching for the low-energy mode gave the Gumbel's distribution I type.

Previously, Marcak and Zuberek (1994) found that the ECD of shocks from the Upper Silesian Coal Basin can be fitted better under assumption that the observed ECD is a result of the imposition of two independent asymptotic distributions different for low-energy and high-energy modes.

Tab.1. Energy distribution functions of strong seismic events for individual regions of USCB.

Regions	Modes	Gumbel's distribution parameters				Statistical parameters		
		$y(E)$	K	ε	v	Merit function	Curvilinear correlation coefficient	Explained variance
MS	L	$E - 178\,563{,}7$	1	-	178 563,7	0,002435800	R= 0,99685	99 %
MS	H	$\ln\left(\dfrac{E}{42\,317{,}8}\right)^{-0{,}7705}$	- 0,7705	0	42 317,8	0,000203723	R= 0,99014	98 %
KS	-	$\ln\left(\dfrac{E}{90\,966{,}1}\right)^{-1{,}9845}$	- 1,9845	0	90 966,1	0,001498649	R= 0,99849	99 %
RCD	-	$\ln\left(\dfrac{E}{250\,328{,}1}\right)^{-1{,}4471}$	- 1,4471	0	250 328,1	0,005849714	R= 0,99825	99 %
MA	L	$\ln\left(\dfrac{E}{179\,023{,}4}\right)^{-1{,}2166}$	- 1,2166	0	179 023,4	0,002345601	R= 0,99765	99 %
MA	H	$\ln\left(\dfrac{E}{160\,013{,}2}\right)^{-1{,}0927}$	- 1,0927	0	160 013,2	0,005845200	R= 0,99766	99 %
BS	L	$\ln\left(\dfrac{E}{127\,296{,}1}\right)^{-1{,}0032}$	- 1,0032	0	127 296,1	0,001355658	R= 0,99821	99 %
BS	H	$\ln\left(\dfrac{E}{125\,910{,}5}\right)^{-1{,}1966}$	- 1,1966	0	125 910,5	0,000002188	R= 0,98398	98 %

MS - the main syncline area, **KS** - the Kazimierz syncline area, **RCD** - the Rybnik Coal District, **MA** - the main anticline area, **BS** - the Bytom syncline area, **L** –low energy distribution, **H** – high energy distribution, **y** – fitted theoretical function, **K** – distribution coefficient; **ε** – a lower cut in Gumbel's distribution II type; **v** – energy value for which y= 0; **Statistical parameters** from *Statistica*
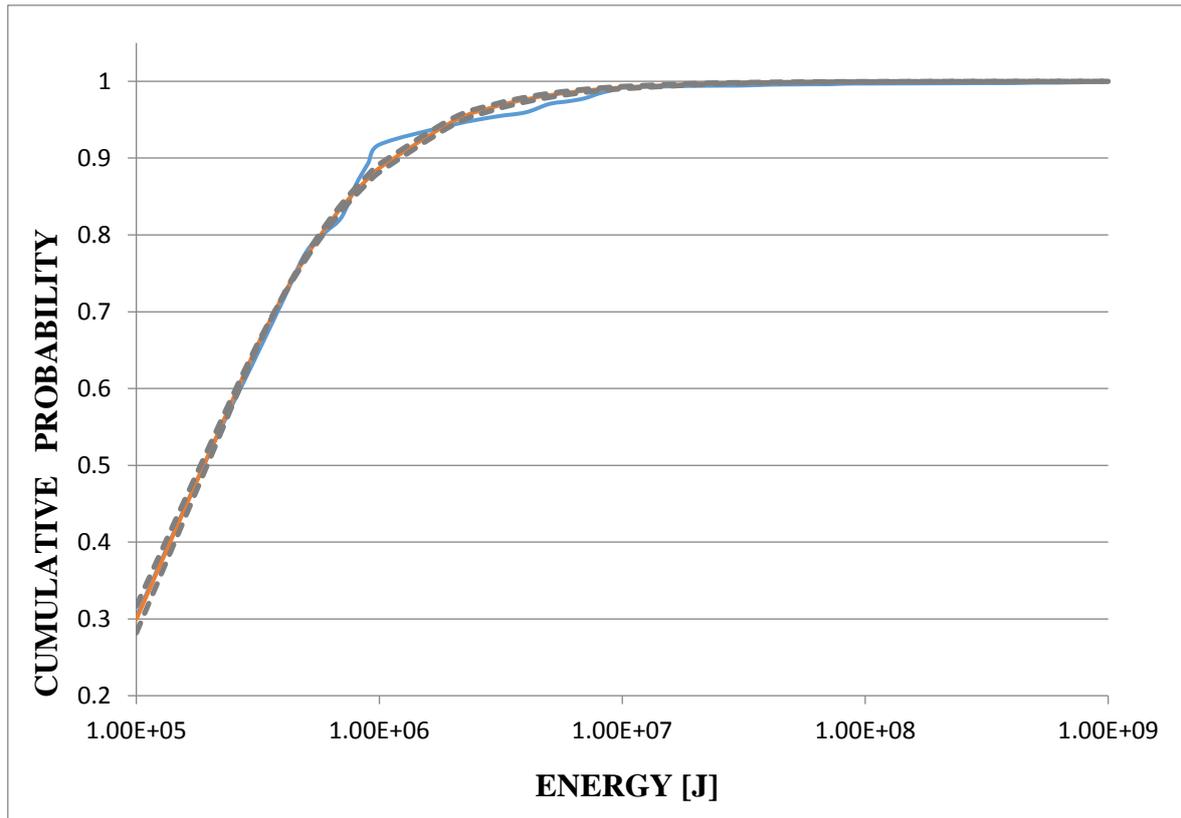
Fig.12. Seismic energy distribution curves from the Bytom syncline region (1987 – 2012). Blue – empirical (ECD), red – theoretical (CDF), greys – 5% confidence intervals for CDF
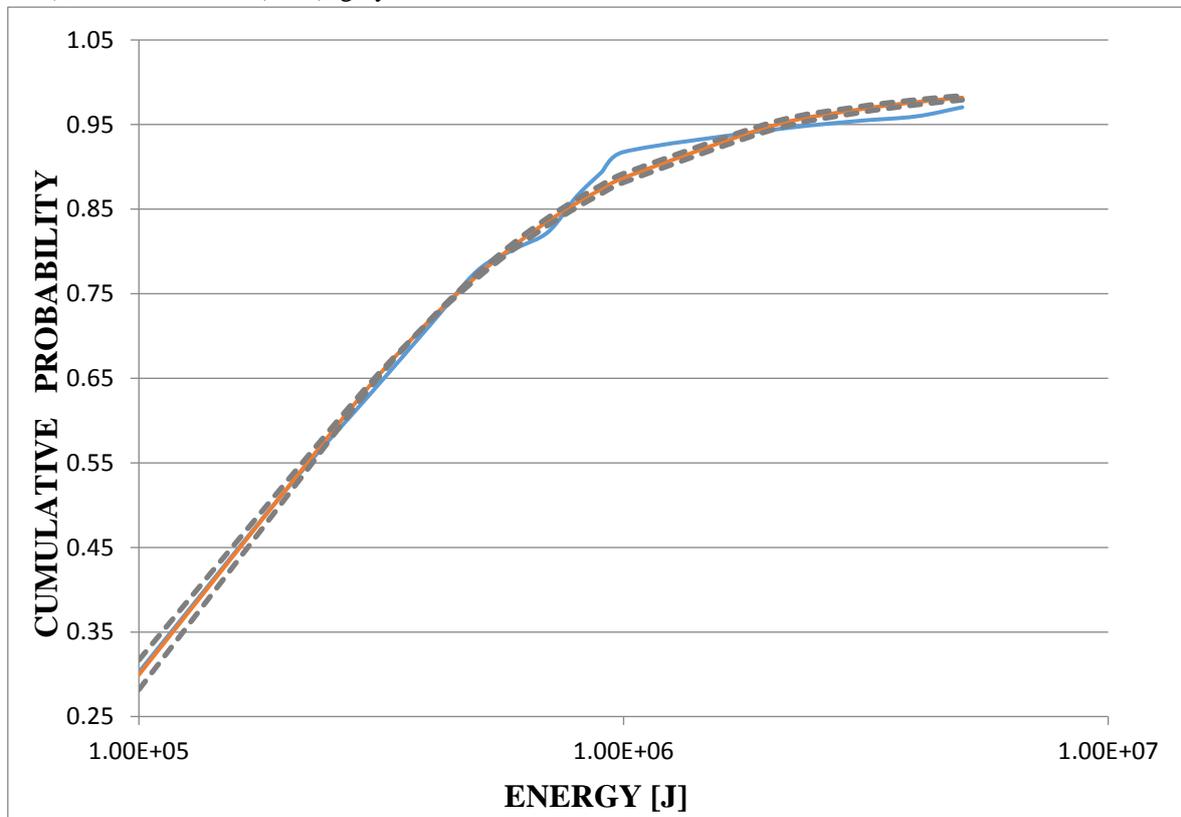
Fig.13. Seismic energy distribution curves for low-energy shocks from the Bytom syncline region (1987 – 2012). Blue – empirical (ECD), red – theoretical (CDF), greys – 5% confidence intervals for CDF
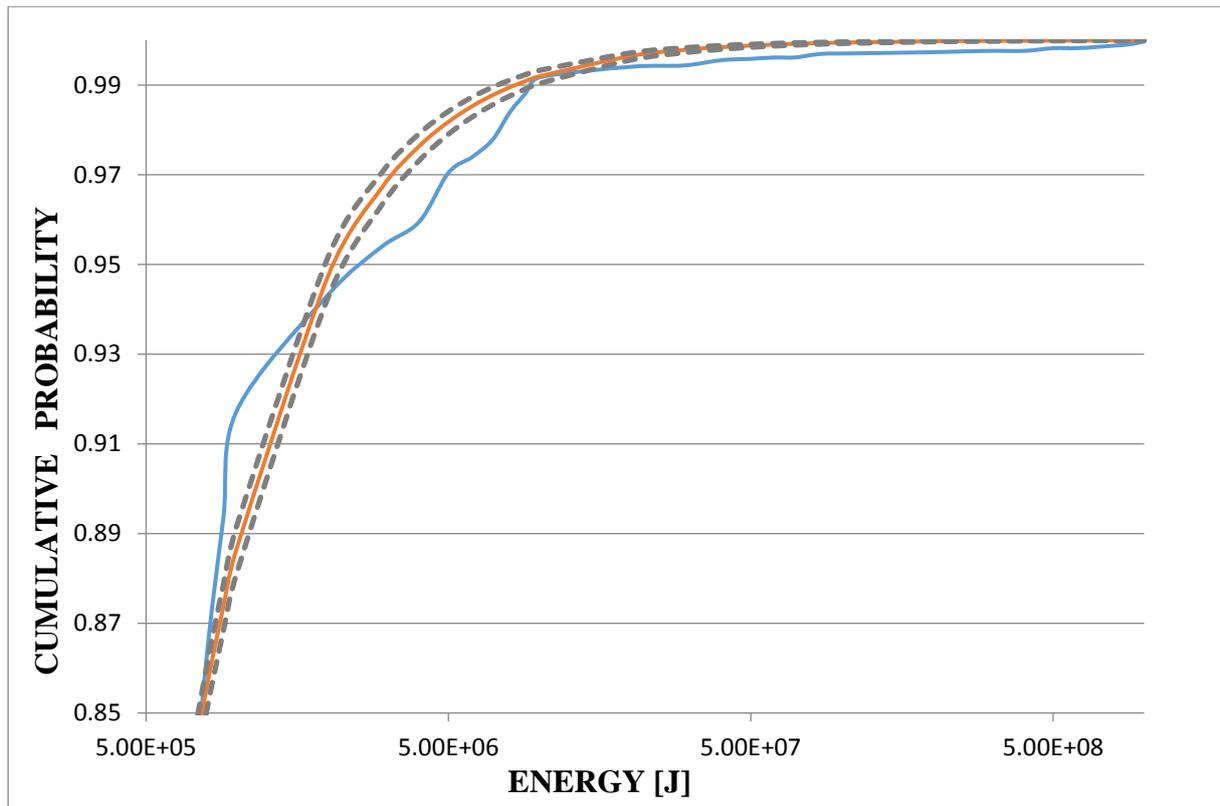
Fig.14. Seismic energy distribution curves for high-energy shocks from the Bytom syncline region (1987 – 2012). Blue – empirical (ECD), red – theoretical (CDF), greys – 5% confidence intervals for CDF

The results obtained in this paper referring to a much wider time window (1987 – 2012) also showed the bimodality of the distributions of seismic energy in three out of five test areas: in the main syncline area, the Bytom syncline area and the main anticline area. It may be indicated by the existence of inflection points on the graphs of ECD and the ability to the relatively good matching of Gumbel's distributions with different parameters for low-energy and high-energy branches separately.

However, in areas characterized by a relatively small amount of high-energy shocks (the Kazimierz syncline area and the Rybnik Coal District) bimodality was not found. The ECD could be fit by a single Gumbel's distribution.

Analyzing the energy distributions of seismic shocks A. Kijko et al. (1987) pointed that the process of events generation is complex and there might be two causes of energy distribution bimodality. One of them is a different mechanism generating shocks in different rock layers with distinct strength properties. The second one can be the impact of additional factors on the occurrence of the strongest shocks, for example − tectonic stresses. The second hypothesis seems to be more credible taking into account later research (Idziak et al., 1991; Gibowicz, Kijko, 1994). Kijko et al. (1987) suggested that the experimental cumulative distribution (ECD) should correspond to the distribution of Gumbel's III type, because of possible limitation in

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maximum shocks energy for both modes. However, their research was based on a much smaller seismic catalog. The results of the analysis of events from the period 1987 – 2012 showed that Gumbel's distribution II type better matched the ECD. It points to the possibility of generations of events with an energy much higher than observed formerly.

The second hypothesis of distribution bimodality is supported by Jura's research (1999) which indicates the natural relaxation of residual tectonic stresses accumulated by tectonic faults, especially in the northern fault side of the Kłodnica fault, where the Young - Alpine tectonic stresses are observed.

Another thing to consider is the depth of event hypocenters distribution. Marcak and Mutke (2013) focused on the Bytom Syncline. The hypocentres of the strongest tremors were located at significant depths (300–800 m under seam 503, from which the coal was mined). Fundamentally, most of the tremors were located much deeper than the mined coal seam more than 1,300 m below the ground surface. They notice that, as the longwall excavation passed through the fold axis, the tremor hypocentres were deepest. The depths of the hypocentres increased markedly. It seems evident that the stresses produced by the geological structure caused the changes in the mining seismicity. In turn Stec (2006) in her study of seismic activity of the USCB suggest that the strongest events from the 'Śląsk' coal mine had hypocentres located 100–150 m deeper than those of the weaker events. Such a feature of seismic event occurrences is rare in mining-induced seismicity. Confirmation of the accuracy of mine

tremor source depth determination was attempted based on the errors of seismic moment tensor determination. The calculation of the seismic moment tensor for the seismic events from a depth interval of 600–900 m has been performed. The best solution were obtained for the depth interwal of 800–850 m. This confirms the argument that mine tremor sources are located beneath the mining level of 700 m. These facts may indicate that the cause of the strongest tremors can be cumulation of exploitation and tectonic stresses acting in the same parts of the rock mass. Both works supported the hypothesis of tectonic stress realease in case of strong seismic events in Upper Silesian Coal Basin.

Studying seismic energy distributions we should be aware because of certain limitations resulting from the used method of calculation. According to Idziak et al. (1991), analysis of compliance of the empirical distribution with the assumed theoretical distribution may not lead to far-reaching conclusions, since they are purely statistical. Theoretical distribution is matched as part of the empirical distribution, and may show incompatible outside the tested range of energy. Using Gumbel's distribution II type to fit the lower branches of the energy distributions may suggest the existence of a lower limit of shock energy and the lack of restrictions for upper energy limit. In fact, the lower limit is determined by the approved registration threshold and the upper limit, assuming operational origin of shocks, is due to the physical premises.

Another limitation in the interpretation of seismic energy distribution is a small amount of shocks, which are classified as high-energy mode. Distribution parameters

for high-energy mode are calculated on the basis of a small amount of shock, so it can significantly affect the results of analysis.

The results of presented study have confirmed the existence of bimodality of the distributions but the reasons for its existence are not fully explained. As it have been suggested by other authors, high-energy mode can be related to tectonic activity. Currently, the author has been working on checking whether the strongest shocks are related to the seismic activity of areas without the USCB, especially in the south of Europe. However, the resolution of this problem is very difficult and up to this day we still could not get a clear position on this issue. It requires further study going beyond the USCB and statements whether the tectonic activity and the geodynamics of areas located south of the USCB affects the strongest shocks.

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