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HEURISTIC MODEL OF MULTIMODAL ENERGY–FREQUENCY DISTRIBUTION IN MULTISTRATIFIED ENVIRONMENT IN PRIMARILY STRAIN–HOMOGENEOUS AREAS

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Abstract. The parameter changes of theoretical distributions (Paretto, Weibull) are often used for short–term prediction of strong [illegible]
The real observed [illegible]
these theoretical dist[illegible]
simple [illegible] conditio
weak [illegible] layers
All parameters of [illegible] – [illegible]
upper limitations and E – F distribution [illegible]
upper limitations of E – F distribution have not any prediction abilit[illegible]
tremors, but they are connected with the apparatus sensitivity and thicknesses of the hanging wall layers respectively. The develo[illegible] – [illegible]
modelled in case of coalface advancement [illegible] – [illegible]
sl[illegible] iown that the
Such a development of [illegible] – [illegible]
layers. [illegible]
seismic activity and that of the whole coalface [illegible]

1. Introduction

Statistical prediction is based on statistically significant changes in the observed parameters of seismic activity. These changes reflect the stress changes in the observed massif area, where the seismic events are registered. Two of the most frequently used parameters of seismic activity [illegible] energy–frequency (E – F) distribution slope (Gibowicz, 1979) and the seismic activity. Both the parameters can be observed simultaneously in such a manner that the real data of E – F distribution are interleaved with some of the theoretical distributions (Weibull, exponential, Paretto, Paretto's truncated, polynomial and Lasocki, 1993a; 1993b).

Statistical prediction is based on interpretation of the changes in parameters such as fractal dimension (Mortimer, 1997; Lasocki and Mortimer, 1996), spatial nonrandomness, spatial correlation dimension, spatial clustering (Eneva, Villeneuve, 1997), maximum or medium height of the events [illegible] 1999a), the velocity coefficient drop of aftershock sequency, the slope of aftershock sequency after blasting or coal extraction activities (Kalenda, 1992; Kornowski, Wasko, 1998) with the rockburst occurrence.

In this paper we will deal with the E – F distribution parameters in real environment of the Ostrava–Karviná Coal Basin (OKCB), which have some influence on statistical prediction [illegible] ment of E – F distri [illegible] assumption of homogeneous primary strain state and the multilayer environment.

2. ANALYSIS OF E – F DISTRIBUTION PARAMETERS IN CONDITIONS OF MULTILAYER ROCK MASS

The simple E – F distribution [illegible] described by four independent parameters [illegible]

- low energy limitation E_d
- high energy limitation $E_{\max}$
- slope b of linear part of E – F distribution
- absolute term a of distribution line

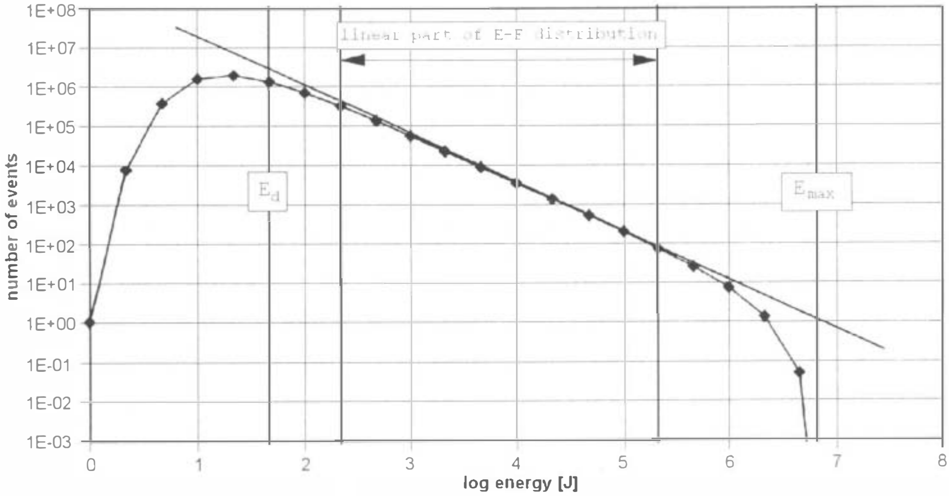

FIG. 1. Energy–frequency distribution of single layer

2.1. [illegible]

In the case of E – F distribution there must exist some low limitation, because in the opposite case the bulk of accumulated energy would have [illegible] a bulk unit of the [illegible] infinite).

The low limitati [illegible] following consideration: We know the E – F distribution [illegible] a coal seam ($b = 1.5$) and we know the maximum of the observed seismic loading

in a 3 m thick coal seam in a square sized 20 × 20 m, which is about $2000\sqrt{J}$. The seismic loading is defined as a sum of square root of energy
defined area.
reformed coal seam in front of the advancing coalface, in the zone with the increased stress occurring in front of this coal
events in the sensitivity
for the seismic events with energies higher than 2 J. Based on this presumption the absolute term

$$\log N = a - b \log E \tag{1}$$

so that this term can be accepted

$$SZ = 2000\sqrt{J}\,, \qquad \text{where} \tag{2}$$

$$SZ = \mathrm{sum}\begin{cases} 0 & N_i < 1 \\ \left(N_i \cdot \sqrt{E_i}\right) & N_i \geq 1\,. \end{cases} \tag{3}$$

where E lies between classes $E_{\min} = 2\,\mathrm{J}$ and $E_{\max} = 10^5\,\mathrm{J}$. The value of the absolute term of distribution line was estimated according to terms (1)–(3) to 3.3 (see Fig. 2).

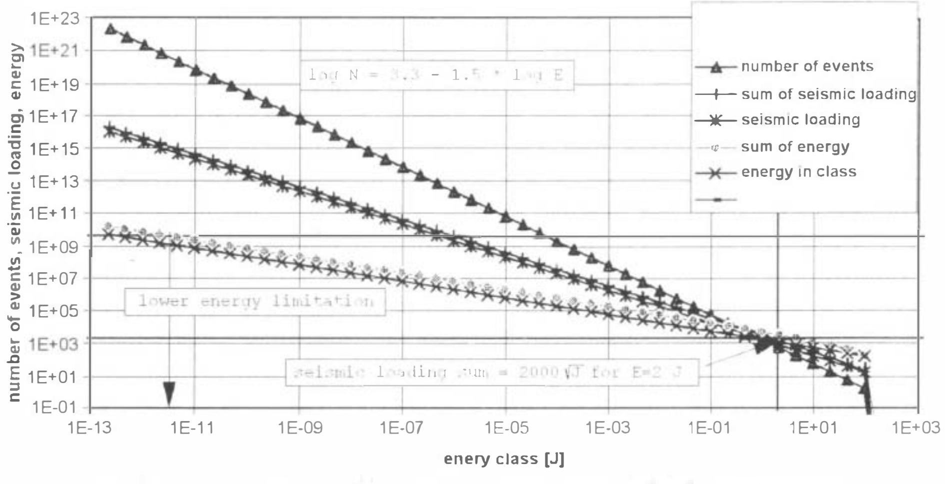

FIG. 2. Evaluation of lower energy limitation of E – F distribution

Next we searched such a low limitation of the distribution line that could fit the total seismic energy in a block sized 20 × 20 × 3 m, released by events with energies ranging from low energy level above the threshold energy E_d up to the maximum energy E_m, in which a number of events in this energy class is less than 1, equalling the
accumulate up to
can accumulate up to 3.0 GJ of this energy of elasticity. By releasing all the energy

of elasticity [illegible] – F distribution
straight line will be

$$\log N = 3.3 - 1.5 \log E \tag{4}$$

the low threshold energy $E_d = 2.5 \cdot 10^{-13}$ J. By partial release of the elasticity
energy in the [illegible]
have a higher value.

The low limitation of E – F distribution in the energy range around 10^{-13} J is connected with dimensions of the smallest structural parts, which a massif is composed of.

In the case of seismoacoustic or seismologic monitoring [illegible]
in the range of about 1 – 1000 J, or in higher than 50 J, respectively, the lower
limitation of E – F distribution [illegible]
apparatus (Kalenda, 1996b). On the basis of this low limitation there is no way
how to predict the [illegible]
model describing the seismic activity should not [illegible]
distribution. That is why it [illegible]
distribut[illegible]
F distribution above its lower limitat[illegible]
E – F distribution models above their low limitations, preferably by the truncated
functions, which merge into linear functions in their lower parts.

2.2. *High Limitation of E – F Distribution*

The high limit [illegible]
however, it reflects [illegible]
zone of the [illegible]
earthquake (Kijko, Sellevoll, 1989) and also under conditions of induced seismicity
(Kijko, Drzezla, Mendecki, 1986).

When monitoring [illegible]
It resulted in investigating the strata thicknesses that affect this high limitation of
E – F distribution. This limit was traced up for sandstones and conglomerates
(the hardest [illegible]
200 m. The strongest [illegible]
the rockburst [illegible]
approx. 200 m between the 37th and 33rd seams above the coalface No.13733. This
dependence can be described by the [illegible]

$$\log E_{\max} = 4.29 \log h - 0.56\,. \tag{5}$$

As it [illegible]
strongest induced events, [illegible]
earthquake [illegible]
from induced seismicity. In both cases the rough tabular structur[illegible]
and [illegible]
the weaker energy range equation (5) was not [illegible]

values were also found wit
1996; Lokajíček, Přikryl, Rudajev, 1996), where dominant energies, included in E–F distribution.
between
ranging from 5 – 10, we could transcribe equation

$$\log E_{\max} = 4.29 \log l - 1.41 , \tag{6}$$

where l [m] is the

The wave–lengths were theoretically verified in the vicinity of weak event foci by means of their
500 m the theoretical
according to equation
1999).

The correlat
the given area was also found with the earthquakes (Darragh

The high limitation of E – F distribution is then independent or only partly dependent of the stress in the observed area. It reflects limited dimensions of layers in the area under the influence of the
parameter is not
a parameter

Only the linear part of E – F distribution
st
low and below their high limitations. Except for truncated Paretto distribution, it is not necessary to
leave with this
function)

2.3. *E – F Distribution Slope*

The third
part
strength of massif in the zone of influence of the coalface, and partly with the stress in this area of the massif (Scholz, 1968). Based on model measurements, the slope value should go down with
are close to the maximum stress

In the
behaviour of this parameter, but
dynamic behaviour. Changes in this parameter could be looked on as changes of the stress

Results
haviour of E – F distribution slope was conformable with the modelling done on the rock samples (Lasocki, 1993b; Holub, 1995; Kalenda, 1996a), but on the other
completely fundamental
ter (Kalenda, 1999a). These deviations were observed especially in the multistrata

environment wit
the hanging wall of the coalface.

2.4. *Multimodal E – F Distribution*

Majority of the
or less exact description of real E – F distribution. As the total E – F distribution
in the
segments of the massif (Holub, 1995; Kalenda, 1999b), the
can be of va
simple above said limited distributions and bimodal
for example by Kijko,
(1987) up to
even from the complicated conditions in the 37th strata of the CSA mine.

By means of real in situ measurements it is not possible to separate individual
partial
only the
distributions it would be necessary to localize all
individual layers or strata)

Development of the mean E – F distribution
velopment of the coalface and
E – F distribution development
velopment
area.

3. DESCRIPTION OF THE STRATIFIED MASSIF MODEL AND CHANGES CAUSED IN TOTAL E – F DISTRIBUTION

From SA measurements
hanging wall and the dependence of maximum observed height of seismic events foci on Benioff's graph slope by the development of a coalface. The time increase of Benioff's graph slope and the
on primary stress before extraction in the observed area, is known as well. The seismic activity in individual layers was evaluated by the

(1) Benioff's graph slope of the entire observed area was calculated from the time when the
(2) From the Benioff's graph slope, the maximum height of seismic events above the
(3) Based on the maxim
the seismic activity coefficient for the given strata
(4) Based on thickness and storage capacity of the
which this
(5) From the strength of the
lated.
(6) Based on the Benioff's graph slope and that of E – F distribution
given la

(7) The absolute term in E – F distribution was corrected using the maximum height seismic activity above the coalface (stress attenuation against height) including the limited activity of the given stratum.

Based on seismic monitoring after starting up all the coalfaces in the OKCB basin the following empirical relation between the coal face start-up time and the Benioff's slope has been found:

$$B = 2.24\left[\sqrt{J}/\mathrm{day}^2\right]\cdot t[\mathrm{day}]\,, \tag{7}$$

where $B\left[\sqrt{J}/\mathrm{day}\right]$ represents the Benioff's graph slope from weekly data windows.

Based on SA localization of events occurring above the coalface the following empirical relation between the maximum height in metres of events above the coalface and Benioff's graph slope was derived:

$$h_{\max} = \exp\left((\log B - 0.35)\cdot \ln(10)\right). \tag{8}$$

Seismic activity coefficient A is defined within a span of 0 – 1 as the ratio of the given strata thickness influenced by the coalface $h_i - h_{i-1}$ where h_{i-1} and h_i are low and high limits of the layer above the coalface foot–wall.

$$A = \begin{cases} 0 & h_{\max} \le h_{i-1} \\ \dfrac{h_{\max} - h_{i-1}}{h_i - h_{i-1}} & h_{i-1} < h_{\max} \le h_i \\ 1 & h_i < h_{\max}\,. \end{cases} \tag{9}$$

The maximum limit energy which the given layer can accumulate was calculated with regard to the layer thickness. Since equation (5) was not derived for coal seams but for solid sandstone and conglomerate strata, the limit energy was corrected by considering the accumulation capacity EA [kJ/m^3] for the given rocks, with the average accumulation capacity for sandstone strata, equalling 25 kJ/m^3

$$\log E_{\max} = (4.29\log h - 0.56) + \log EA/25\,. \tag{10}$$

By comparing the E – F distribution slopes in the OKCB with the strength of strata in P pressure, influenced by coalface, the following empirical equation was derived:

$$b = 2.5 - 0.03225\cdot P\,[\mathrm{MPa}]\,. \tag{11}$$

With seismic activity B the following relation between absolute term a_0 and slope b in E – F distribution is:

$$a_0 = b\cdot(1.789 + 0.00715\cdot B) + (0.356 + 0.000889\cdot B)\,. \tag{12}$$

Declining seismic activity towards the hanging wall can possibly be described, with respect to (9), by equation

$$a = A\cdot a_0\cdot \exp\left(1 - \log\frac{h_{\max}}{4}\right). \tag{13}$$

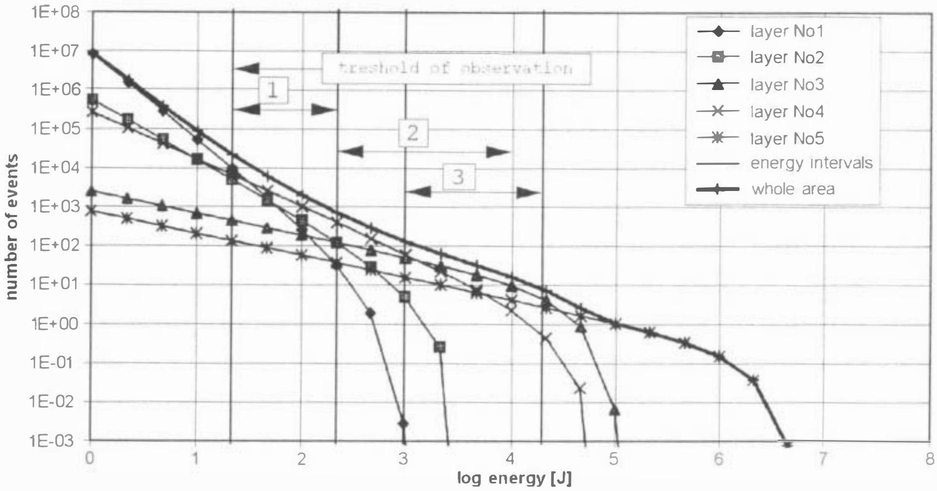

FIG. 3. Multimodal energy–frequency distribution

Based on equations (11) and (13), with respect to (10), the occurrences of seismic events in individual classes were calculated in all layers (see Fig. 3).

4. DISCUSSION ON RESULTS OBTAINED FROM MODELLING THE MULTIMODAL E – F DISTRIBUTION

All events in individual energetic classes for all layers were summed up to get a total E – F distribution (see Fig. 3). The value of the slope of the linear part of E – F distribution was calculated in three commonly used energy intervals (see Fig. 3):

1) — (21 – 2154 J) — for low energy events - mainly from the coal seam
2) — (215 – 10000 J) — for the proportion of coal to hanging wall seismic activities
3) — (1000 – 21540 J) — to monitor the hanging wall events.

The method of interleaving the distribution lines does not have any significant impact on the resulting relative values of the distribution line slopes b. The forms of E – F distribution lines in individual stages 2 – 5, according to Fig. 4, when higher and higher strata become active, are shown in Fig. 5a – d. These figures show different types of E – F distributions in the way they were described according to in situ measurements in the OKCB and elsewhere in the world (see above), from the simple linear distributions, and simple limited ones, to bimodal limited distributions and multiple ones.

With gradual activation of the hanging wall strata up to the maximum, with the condition of constant primary stress, we could see that the total E – F distribution was continuously changing, which should respond to the stress changes. The changes in E – F distribution slope in all its sections (from low to high energy areas) are not monotonous. They respond to the actions of individual layers even during the period when primary stress around the coalface is not changing. When solid strata become active, the total E – F distribution slope goes down but, conversely,

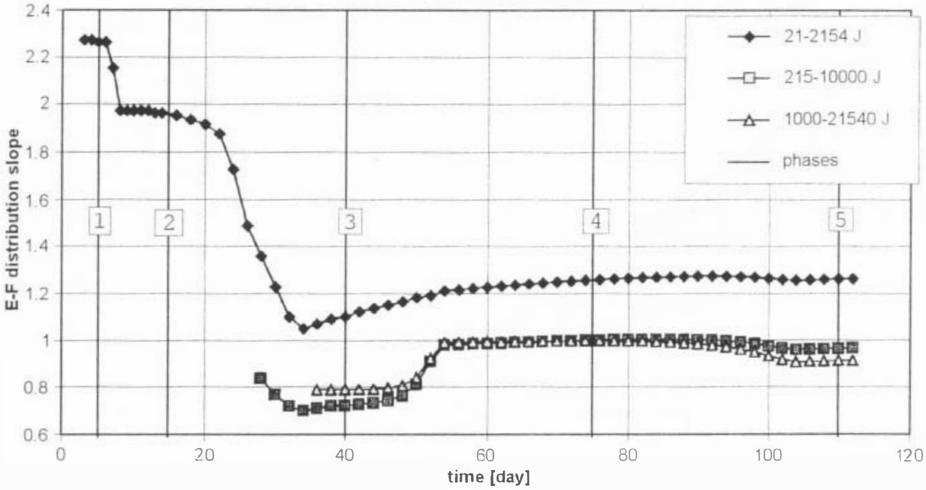

FIG. 4. Development of energy–frequency distribution slope

when less solid strata become active, this slope goes up, which might mislead to a presumption that the primary stress in the observed area goes down.

Because the advancement of activity towards the hanging wall is proportional to a logarithm of the Benioff's graph slope, it holds true that the advancement of maximum height of events observed above coalface towards the hanging wall is gradually decelerating to the stage until the top heights get over the next layer boundary–line. In this case we can talk about reaching the limit activity of the layers in the coalface hanging wall. All the higher layers will only get flexured, but they will not be disrupted and seismic events coming from these layers will not be observed. Based on the OKCB's experience the maximum heights of events were observed about 200 m above the coalface, the mean maximum heights of events above the coalface, with about 3 m of extracted thickness, range from 20 – 30 m. A similar situation is in the horizontal direction where it is possible to talk about reaching the maximum dimensions of the area of influence caused by a coalface.

When comparing the seismic activities of individual layers of the model found in the stage of a developed coalface (i.e. when the activity has reached its maximum) it was shown that higher layers with lower strength had a higher seismic activity with comparison to the lower layers with higher strength. That was also observed by the physical modelling with equivalent materials (Machálek, 1984; 1985).

From the modelling of multilayer environment in specific cases of the OKCB we can see that the increase of height of coalface influence, as a result of starting up the coalface and increased stress in this part of massif, causes the increase in the value of E – F distribution slope in its linear part. This paradox really made impossible to predict the stress state in the case of all coalfaces in the 4th coal block of the CSA mine and it was necessary to use the parameters depending only on the seismic activity which responded proportionally to the stress (Kalenda, 1999a).

With the stress increasing around the coalface, the slopes of all individual E – F

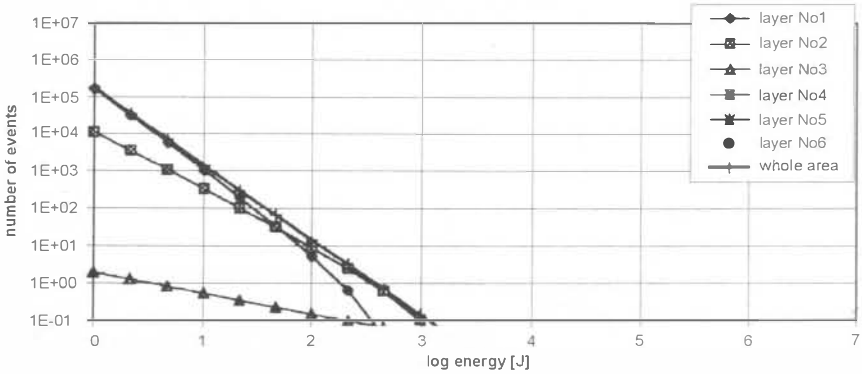

FIG. 5a. Energy–frequency distribution 15 days after beginning of excavation

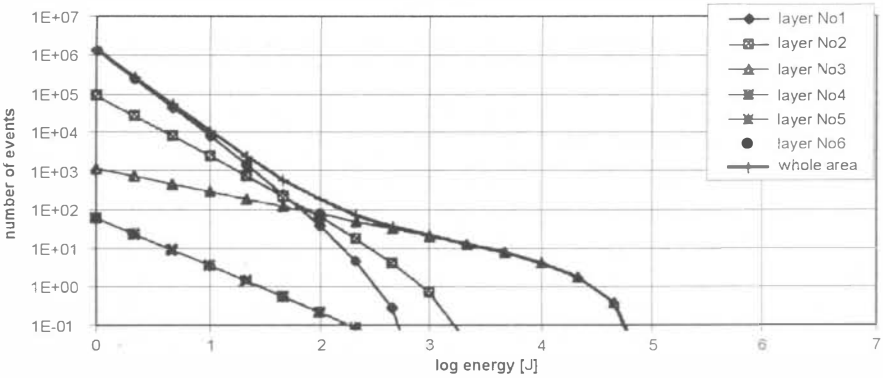

FIG. 5b. Energy–frequency distribution 40 days after beginning of excavation

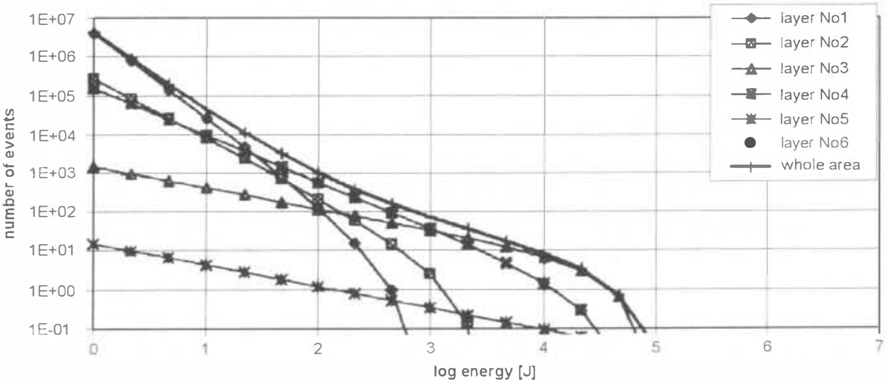

FIG. 5c. Energy–frequency distribution 75 days after beginning of excavation

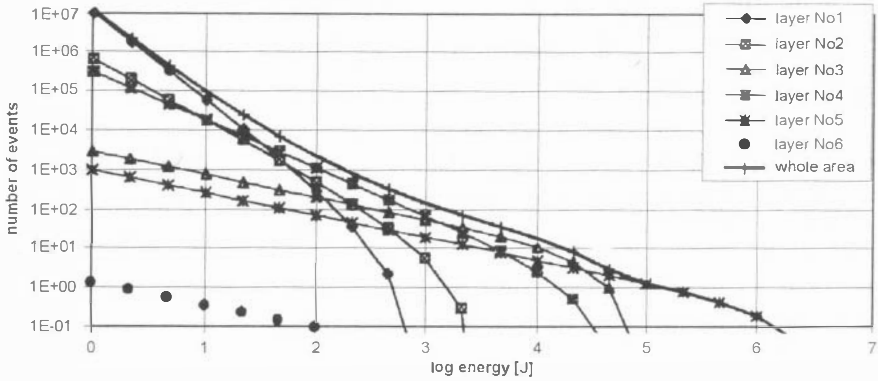

FIG. 5d. Energy–frequency distribution 110 days after beginning of excavation

distributions go down together with the measurements performed on the samples (Scholz, 1968), but their decline is not significant enough to outbalance the changes in E – F distributions caused by the activity of the upper layers of a lower strength.

Modelling the changes in E – F distributions have brought the following conclusions for the tremors prediction:

- before the coalface is started up it is necessary to check by modelling how the E – F distribution slope may behave before the coalface is in its development stage, and what influence will result from higher stress in the area to the changes in height of the foci above the coal seam.
- in case of an unmonotonous change in E – F distribution slope it is necessary to establish the prediction on other parameters such as the mean or maximum heights of events above the coalface, seismic activity, the relation between the activities in coalface and hanging wall, etc.
- in case that the coalface area is monitored by means of a seismoacoustic method and a relatively exact location of foci is known, it is possible to monitor the changes in E – F event distributions for individual layers. However, monitoring of the relative activities of individual layers, always reflecting the stress changes in the area, seems to be more convenient parameter.

5. CONCLUSION

For the prediction of energetically significant seismic events by means of E – F distribution its low and high limitation parameters are not important. Both the parameters reflect, above all, the geometric properties of the given layer or stratum and/or the measurement sensitivity and they do not depend on the stress state of the massif in the given area and time.

The model of stratified rock environment with the horizon of well caving rock showed that a change in E – F distribution occurs during the development stage of a coalface. However, this change is not proportional to stress. It increasingly reflects the participation of individual layers in total seismic activity, which in extreme cases may make any prediction by E–F distribution impossible. This result is valid not only for the environment of the Ostrava–Karviná Coal Basin but also for any multilayer environment.

Prior to monitoring the coalfaces and predicting important seismic events it will be necessary to model the development of E–F distribution slope and find out whether this prediction is possible or convenient under given conditions.

Afterwards it will be necessary to model real environments and changes in E–F distribution with stress alterations in the developed stage of a coalface (i.e. when the magnitude of coalface influence and seismic activity do not substantially change), or under the most complicated conditions, when there are stress changes during the coalface development stage.

REFERENCES

Darragh R.B., Bolt B.A.: 1987, A comment on the statistical regression relation between earthquake magnitude and fault rupture length. *BSSA* **77**, No.4, 1479–1484.

Eneva M., Villeneuve T.: 1997, Retrospective pattern recognition applied to mining–induced seismicity. In: *Rockbursts and seismicity in mines*, Gibowicz, Lasocki eds.

Gibowicz S.J.: 1979, Space and time variations of the frequency–magnitude relation for mining tremors in the Szombierki coal mine in upper Silesia,Poland. *Acta geophysica Polonica* **XXVII**, No.1, 39–49.

Holub K.: 1995, Analysis of *b*–value in the frequency–energy distributions. *Publ. Inst. Geophys. Pol. Acad. Sci.* **M–19** (281), 153–162.

Kalenda P.: 1992, *Zhodnocení závislosti vyzařované seismické energie na parametrech horninového prostředí a technologii dobývání*. Disertační práce ČS.Akademie věd.

Kalenda P.: 1996a, Analysis of the prediction possibility of strong mining induced seismic events in Ostrava–Karviná Coal Basin on the basis of seismological method. *Proc. of "Tectonophysics of Mining Areas" – International Scientific Workshop*. Prace Naukowe Univ. Slakiego, Nr. 1602, Katowice, 145–161.

Kalenda P.: 1996b, A contribution to discussion on lower limitation of energy–frequency distribution. *Acta Montana* **A9** (100), 131–138.

Kalenda P.: 1999a, Rozbor predikčních parametrů v podmínkách porubu 14736 na Dole ČSA. *Uhli, rudy, geol.průzkum* **1/99**, 6–12.

Kalenda P.: 1999b, Comparison of SA and SL energy–frequency distributions. *Publ. Inst. Geophys. Pol. Acad. Sci.*, in print.

Kalenda P., Veselá V.: 1999, The dependence of forms of spectra on the distance and energy value. *Publ. Inst. Geophys. Pol. Acad. Sci.*, in print.

Kijko A., Drzezla B., Mendecki A.: 1986, Bimodalny charakter extremalnych rozkladow zjawisk sejsmicznych w kopalniach. *Publ.inst.geoph.Pol.acad.Sc.* **M–8** (191), 91–101.

Kijko A., Drzezla B., Stankiewicz T.: 1987, Bimodal Character of the Distribution of Extreme Seismic Events in Polish Mines. *Acta Geophysica Polonica* **XXXV**, No.2, 157–166.

Kijko A.,Sellevoll M.A.: 1989, Estimation of earthquake hazard parameters from incomplete data files.Part I.Utilization of extreme and complete catalogs with different threshold magnitudes. *BSSA* **79**, No.3, 645–654.

Knoll P.: 1989, The fluid–induced rockburst of March 13, 1989 in the Werra potash mining district of the GDR. *Proceedings of the Symposium of prognose and prevention of the rockbursts*. CIPE Publ. No.1831.

Kornowski J., Wasko A.: 1998, Application of a rheological rock model for stress changes estimation from a series of seismoacoustic measurements. *Publ.inst.geoph.Pol.acad.Sc.*, in print.

Lasocki S.: 1993a, Statistical Prediction of Strong Mine Tremors. *Acta Geophysica Polonica* **XLI**, No.3, 197–234.

Lasocki S.: 1993b: Statistical short-term prediction in mining induced seismicity. In: YOUNG R.P. (ed.) *Rockbursts and Seismicity in Mines 93*. 211–215.

Lasocki S., Mortimer Z.: 1996. Variations of ms source distribution geometry before a strong tremor occurrence in mines. *Proc. of the 6th conference on acoustic emission/microseismic activity in geologic structures and materials*. The Pennsylvania State University. 11.–13.6.1996.

Machálek M.: 1984. *Zpráva o výsledcích 1. modelového pokusu řešícího v řezu J – S geomechanické problémy 3. kry Dolu ČSA v Karviné*. Zpráva VVUÚ, Ostrava.

Machálek M.: 1988. *Zpráva o výsledcích 7. modelového pokusu řešícího v řezu Z – V geomechanické problémy 3. kry Dolu ČSA v Karviné*. Zpráva VVUÚ, Ostrava.

Mortimer Z.: 1997. Fractal analysis for the local induced seismicity in some Polish coal mines. In: *Rockbursts and seismicity in mines*. Gibowicz, Lasocki eds.

Petroš V.: 1997. Stress distribution in exploited rock mass. *Sborník prací VŠB*. No.1. XLIII. 25–.

Rudajev V., Lokajíček T., Číž R.: 1996. Structure elements of rocks and energy–frequency distribution of seismic phenomena. *Acta Montana* **A9** (100). 121–130.

Scholz C.H.: 1968. The frequency–magnitude relation of microfracturing in rock and its relation to earthquakes. *BSSA* **58**. No.1. 399–415.

Speidler D.H., Mattson P.H.: 1993. The polymodal frequency–magnitude relationship of earthquakes. *BSSA* **83**, No.6. 1893–1901.

ABSTRAKT

Pro krátkodobou statistickou predikci významných otřesových jevů jsou často užívány změny parametrů teoretických distribucí (Paretto, Weibull) (Lasocki, 1993a), kterými je prokládána pozorovaná energeticko–četnostní (E – Č) distribuce seismických jevů. Tato statistická predikce dává dobré výsledky v jednoduchých podmínkách. V mnohovrstevnatém prostředí, kde se v nadloží porubu střídají vrstvy pevných a méně pevných hornin, jsou výsledky nejednoznačné.

V práci byly rozebrány všechny parametry E – Č distribuce: její dolní a horní omezení a směrnice. Bylo ukázáno, že dolní a horní omezení E – Č distribuce nemá význam pro predikci významných otřesových jevů, ale je dáno citlivostí měřicího systému resp. mocností vrstev a souvrství ve vlivu porubu. Byl modelován vývoj směrnice E – Č distribuce při rozvoji porubu v podmínkách statického homogenního napětí v oblasti, kdy se střídala období poklesu s obdobími nárůstu směrnice. Tento vývoj byl určen výhradně změnami aktivity jednotlivých vrstev v nadloží porubu a jejich podílem na celkové seismické aktivitě v oblasti porubu.