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STATISTICAL ANALYSIS OF SEISMIC EVENTS INDUCED BY THE UNDERGROUND MINING

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Abstract: The paper is intended as an analysis of the relation between seismic activity and geological structure of the overlying complexes. Its results are illustrated by the example of the coalface No.13933 in the 3rd tectonic block at the ČSA Colliery in Karviná. The development of the energy-frequency distribution in time is investigated as well as the temporal development of the theoretical and actual values of the maximum energy of a single event . The development of the Benioff's summation graph is analysed and it is divided into seven phases.

Key words: Coal mining induced seismicity, seismic energy release, energy-frequency distribution, spatial and time emission variations, Ostrava-Karviná Coal Basin.

1. INTRODUCTION

Radiation of seismic energy is one of the principal responses of the rock mass to mining activity. For purpose of monitoring the seismic activity in the eastern part of the Ostrava-Karviná District (OKD), the local seismological network is used especially to investigate the areas with increased rockburst hazard. The results of seismological observations are in the course of the time stored to the database and used to diurnal estimation of the rock mass state within the framework of the geomechanical service at individual collieries.

In this paper, statistical analysis of seismic events, induced during the whole period of excavation of the coalface No.13933 in the 3rd tectonic block at the ČSA Colliery in Karviná since January 1, 1990 to November 24, 1991, is performed. The results obtained are in close relation to those of the work of Kalenda et al. 1990a. This work was presented at the 20th Czech-Polish Conference on selected geophysical problems in mines, 1990 and its topic was intended as a hitherto statistical analysis of the first four months of excavation of the coalface No.13933.

From the point of view of the present evaluation, the preliminary results were fully acknowledged. They concerned both estimation of the maximum possible energy of a single event depending upon the thickness of an overlying layer and development of seismic activity during the uniform advance of the coalface.

The importance of analysis of the seismic energy released during excavation of the coalface No.13933 is emphazized by the fact that this energy represents in the Benioff's graph for the whole eastern part of the OKD for the period January 1, 1990 - November 24, 1991 the quotient of 30 per cent.

Under the term of a coalface, the coalface No.13933 is ment implicitly in the whole paper.

2. SEISMIC OBSERVATION SYSTEM

Seismic activity during excavation of the coalface was observed by underground and surface stations of the local seismological network equipped by the DSLA instruments. The data of these stations formed a basis for localization of the events recorded and for determination of their seismic energy which is performed in the Operational Seismological Centre at the ČSA Colliery in Karviná. As complementary data in the central processing, the data of stations of the seimic polygon were used (Fig.1).

It follows from geometry of the stations distribution that events induced by excavation in the coalface are inside the registration base. The data of the A6 and A7 surface stations, mounted above the excavated coalface, made possible to compute the vertical coordinate of a focus.

Under assumption of simultaneous registration of an event by at least three stations, the detection capability of the local seismological network within the area investigated was defined by the value of 20 J.

The localization capability was influenced namely by accuracy of arrival time determination for the P and S waves, as well as for the phase with the maximum amplitude, by the propagation velocities of these wave groups in the rock mass and by the given distribution of stations. In the area of the coalface and its surroundings, the localization error in the horizontal plane was less then 100 m. Determination of the vertical coordinate was only reduced to the resolution if the event originated in the level of excavation or in the higher roof.

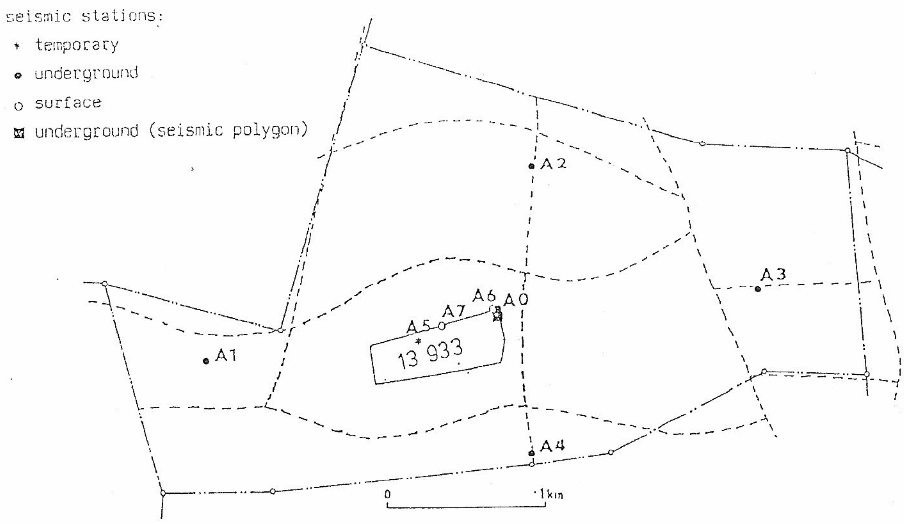

Fig. 1. Distribution of stations of the local seismological network and the seismic polygon in the surroundings of the coalface No.13933 in the 3rd tectonic block at the ČSA Colliery in Karviná.

Energy of events, recorded in the range of 20 J to $2x10^6$J, was determined with accuracy to one energy class M, related to the seismic energy E by the following formula

$$\log 0.15 + (M-1)/3 < \log E < \log 0.15 + M/3 \quad . \qquad (1)$$

In the energy interval of 20 J to 100 J, mutual overlap of seismological and seismoacoustical observations, i.e. of two reciprocally independent measuring systems, became apparent (Kalenda et al. 1990). The results of the seismoacoustic localization whose error is much less than of those of the seismological localization, proved the detection and localization accuracy defined above. Computation of energies by both methods was statistically equalized in the overlap interval and further it was extended outside this interval. For events less than 20 J, the energy was calculated from the seismoacoustic data, for events greater than 100 J from the seismological ones.

In addition to the local seismological network and the seismoacoustic monitoring system, there were sensors of the geomechanical monitoring system distributed within the area of the coalface. Based upon the data of the presure gauges, convergometers and extensometers, it was possible to complete the information on stress-deformation zones in the nearest surroundings of the coalface and in its roof (Žák et al. 1990).

3. DATABASE

Seismic events localized during excavation of the coalface were stored to the seismological database. This database contained more than 7500 events from the investigated area during the given period. Radiation of seismic energy was dependent on actual position of the coal face related to the residual pillars in the 33^{rd} coal seam, situated cca 180 m in the roof of the excavated 39^{th} coal seam (Fig.2). The coalface advance during the studied period was quite uniform.

To store the final results to the database, the processing method with maximum reliability was chosen. For example, to determine the vertical coordinate of a focus, the seismoacoustic method was used, and to determine the seismic energy of great events, the output of seismological method was used.

4. DATA PROCESSING AND INTERPRETATION

4.1. Energy-frequency distribution

Energy-frequency distribution (E-F distribution) is defined by the linear function as follows

$$\log N = a * \log E + b \,, \qquad (2)$$

where N - frequency of occurrence of events in the given energy class,
E - mean energy of the given energy class,
a,b - linear, resp. absolute term of the linear function.

It was found that the character of seismic energy radiation in the given area can be exactly described by the values of a,b. Namely the a slope has significance for quantitative expression of the mutual ratio of events with low and high energies.

For the whole OKD, the a slope is equal to -0.76, the linear function (2) is valid in the interval of energy classes of 9 - 24, corresponding to energies of 10^2 - 10^7 J. Evolution of the E-F distribution during excavation of the coalface is presented in Fig.3.

In Fig.3, the quiescent state before the start of excavation is apparent (a=-0.8) as well as the very fast change of the slope to the value of -0.53 during the first six months of excavation as a result of an increased stress state in the rock mass. Since this time, the ratio of events with great energies related to those of small energies is greater than the mean value of the OKD. Hazard of origin of a sudden rockburst is very high and the dangerous states are not indicated by a sufficient number of small events before the proper rockburst.

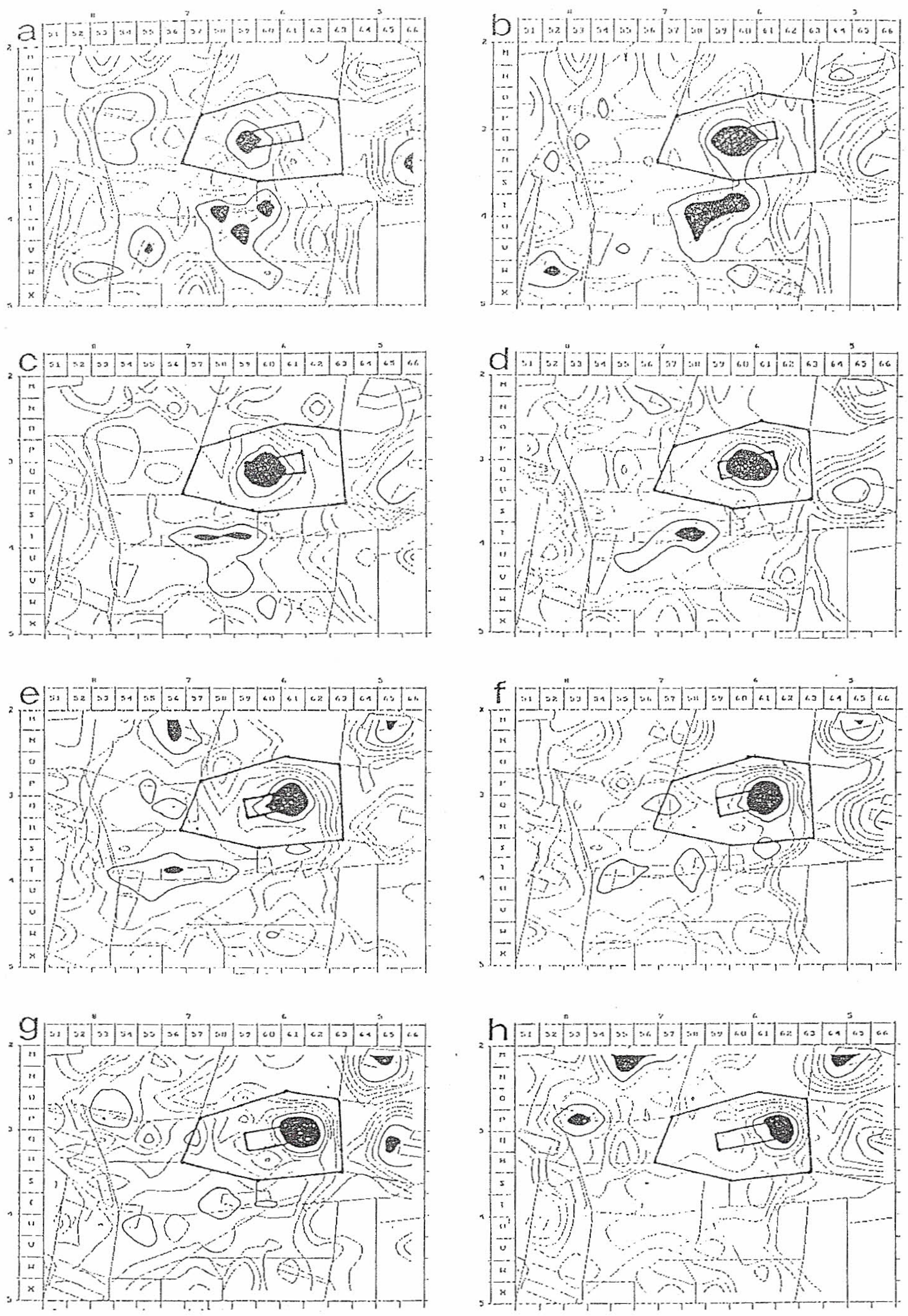

Fig. 2. Radiation of seismic energy in the 3rd tectonic block of the ČSA Colliery and its surroundings in the period since January,1,1990 to December 31,1991 divided into six three-months intervals a)-h). Isolines are in logarithmic scale, the black areas correspond to the Benioff's sum greater than 1000 $\sqrt{J}$/three months. The coalface No.13933, as well as the 3rd tectonic block are marked out by solid lines.

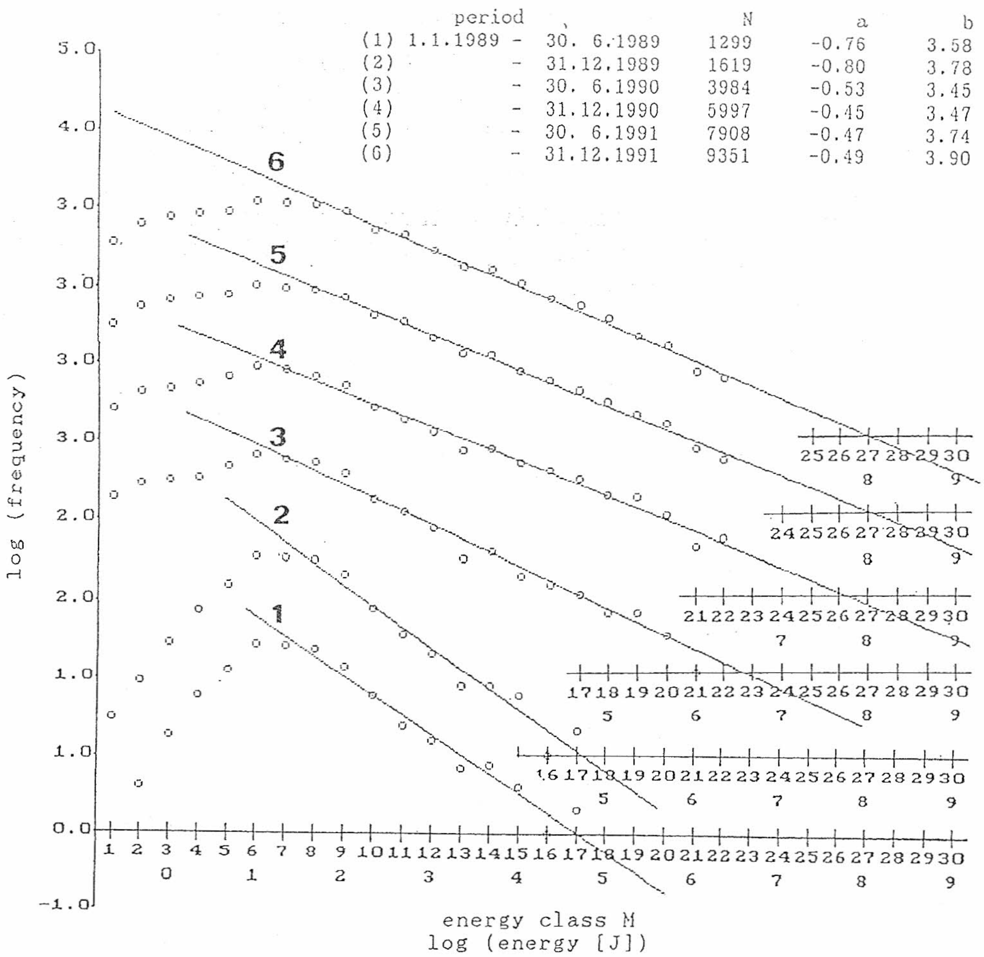

Fig. 3. Energy-frequency distribution for the 3rd tectonic block of the ČSA Colliery in the period of January 1, 1989 to December 31, 1991 divided into six intervals of six months (N - frequency, a,b - parameters of the formula logN = a logE + b).

By computation of time evolution of the E-F distribution with the time step of two days, theoretical values E_t of the maximum energy of a single event were determined. According to the formula (2) by substitution of N = 1, $E_t = \exp(-b/a)$. Computed values of E_t were compared with actual values E_s (see Fig.4a), evolution of the a,b parameters in time is presented, too (see Fig.4b).

Comparison of theoretical and actual values shows that during the first six months of excavation, both values were almost equal. Subsequently the theoretical value raises continuously up to the difference of 1.6 of the decadic order greater than the actual value. This difference demonstrates the fact that only a limited thickness of overlying strata radiated the seismic energy and so, the influence of excavation of the coalface did not become apparent in the whole thickness up to the 33rd coal seam (cca 180 m).

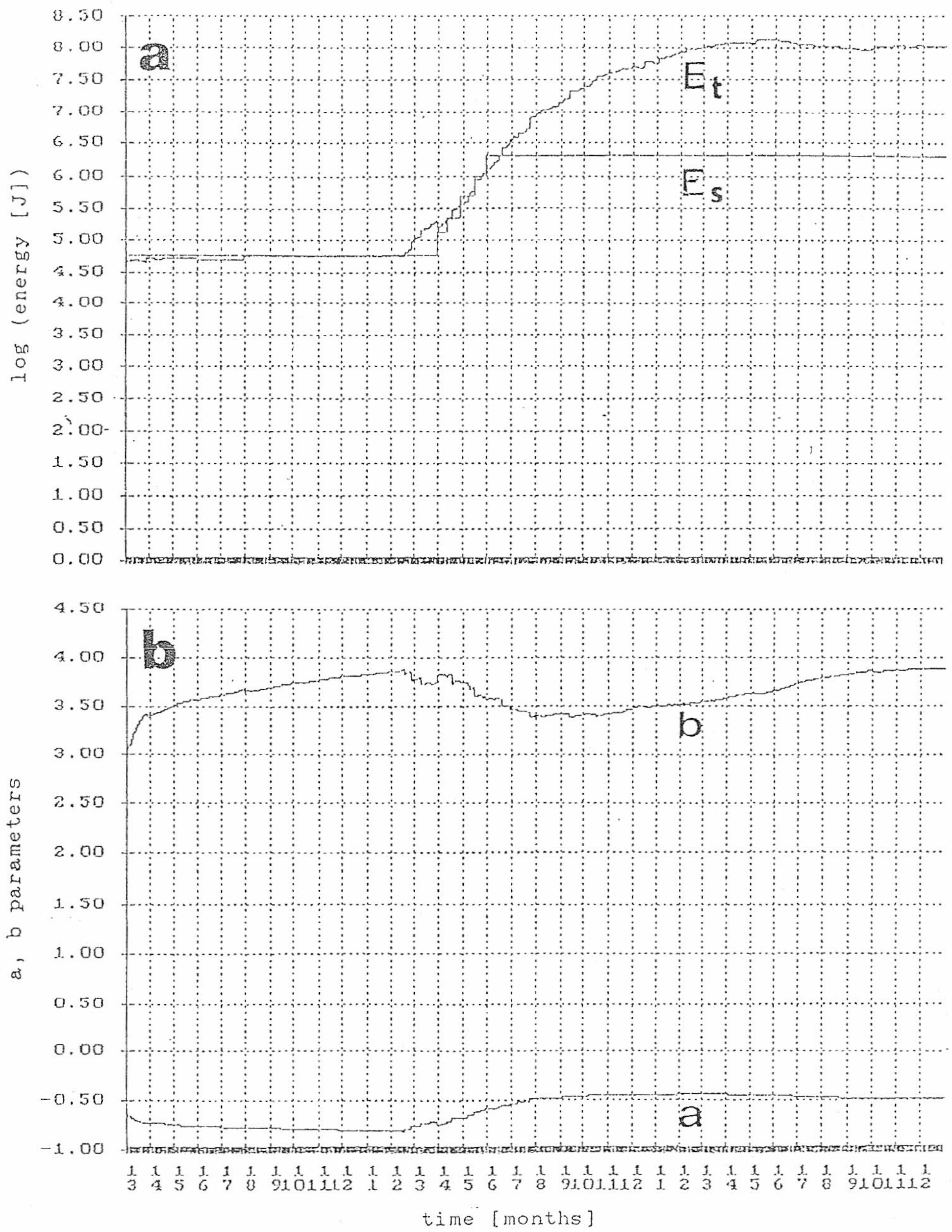

Fig. 4. Development of theoretical E_t and actual E_s values for the maximum energy of a single event (a) together with a,b parameters of the energy-frequency distribution (b). The graphs were calculated for the 3rd tectonic block at the ČSA Colliery using data of events recorded in the period of January 1, 1989 to December 31, 1991.

4.2. Gumbel's distributions of extremal values

Application of the third Gumbel's distribution depends upon the layer, resp. series of strata in the roof for which the extremal value is to be determined. This affirmation is of fundamental importance because any layer, resp. series of strata are characterized by the limited quantity of accumulated energy that can be released by a single event.

The succesful computation of the third Gumbel's distribution is conditioned by:

- existence of the seismological database of events with acccurate spatial localization (horizontally the error up to 100 m, vertically up to 50 m),
- selection of the layer, resp. series of strata, as well as of those events only that originated there according to their vertical coordinate of a focus,
- determination of the basic repeating period for computation of the partial maximum energies. According to the frequency of occurrence, the period of one day to one week can be chosen.

The third Gumbel's distribution for the series of strata above the 39^{th} coal seam together with the low roof of the 37^{th} coal seam brings the limit value of $E_{MAX} = 10^{6.8}$ J. This result is in a very good agreement with the actual maximum energy of $E_{ACT} = 10^{6.3}$ J. Assignment of events to the given series of strata, determined by the vertical coordinate of a focus, is validated by processing the data recorded by the spacial seismoacoustic measuring base.

The results from the area of the coalface contributed to the determination of the dependence of the maximum energy E_{MAX}, released by a single event, on the thickness h of the overlying layer (strata), situated in the influenced zone of the coalface (Fig.5). This empirical dependence can be expressed in the following form:

$$\log(E_{MAX}) = 4.0 \log(h) \quad . \qquad (3)$$

4.3. Benioff's graph

During the period of excavation of the coalface in the years 1990-1991, the outstanding non-uniform radiation of seismic energy was observed. In 1990, about 2.8×10^{7} J were released, in 1991 about 1.1×10^{6} J. However, the diurnal advance of the coalface during the whole period was quite uniform. It follows from this fact that the given differences in radiation can be interpreted as consequence of influence of the two residual pillars in the 33^{rd} coal seam, situated in the roof of the excavated coalface.

While passing under the first pillar during June and July, 1990, the energy release was of 10^{5} J/day, under the second pillar since March to August, 1991, the release was 1.78-times less. Analogous results can be obtained from the Benioff's graph which reaches during the underpass of the first pillar its greatest diurnal increment of 400 $\sqrt{J}$ while under the second pillar the increment of 300 - 350 $\sqrt{J}$/day.

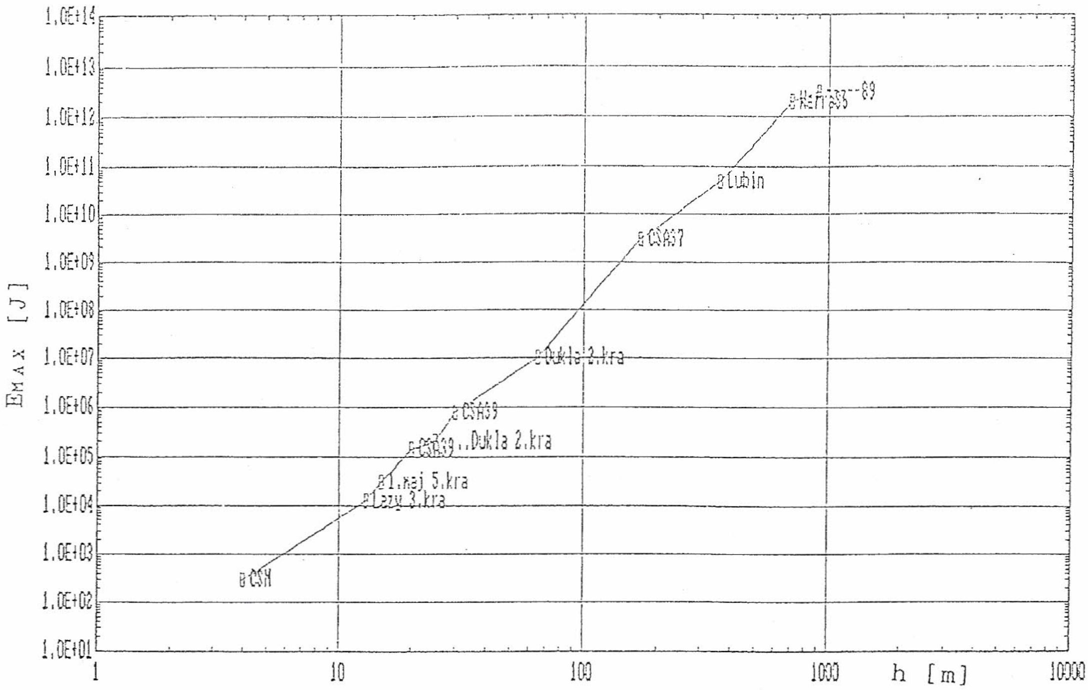

Fig. 5. Dependence of the maximum energy E_{MAX} [J] of a single event on the thickness h [m] of an overlying layer. For the given localities, the limit values E_{MAX} were determined by the third Gumbel's disribution and the following formula was derived: log E_{MAX} = 4.0 log h.

On the other hand, the maximum energies of events from the first and second pillar reached the same value of 2.1×10^6 J. It can be presumed that it is not the excess load that determines the maximum energy of an event, but it is especially the quality of a layer that is as a whole influenced by excavation and which accumulates the energy. The proper excess load plays important role for the velocity of energy release and for the size of the influenced area. In areas without additional stress, events will be radiated from those layers only where the stress is greater than the compressive strength, which is caused by gravitation excess load of the strata influenced by the coalface.

Based upon the Benioff's graph, the excavation of the coalface can be divided into seven periods (Fig.6).

In the first period to February 20, 1990, seismic activity in the whole tectonic block was low (the increment of the Benioff's graph being equal to 5 - 10 $\sqrt{J}$/day). Based upon the results of seismoacoustic monitoring, the increasing excess load of the coal seam was observed, as well as the zone of the moving stress in front of the coalface.

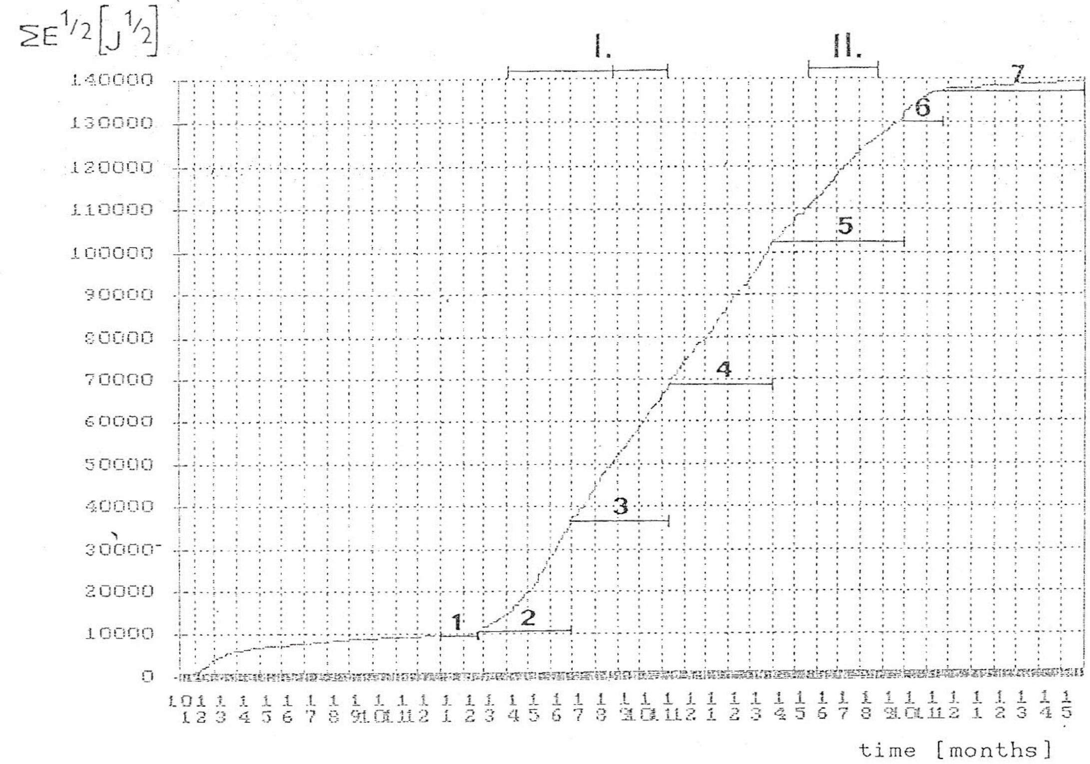

Fig. 6. Benioff's graph for the 3rd tectonic block of the ČSA Colliery during the period of January 1, 1989 to May 31, 1992. Seven partial periods (1) - (7) are marked out, as well as the time of excavation of the coalface No.13933 under the first (I) and second (II) residual pillar in the 33rd coal seam.

During the second period to July 1, 1990, the succesive stepwise increase of the increment of the Benioff's graph is apparent. It was caused by seismic activation of the higher roof over the excavated coalface. Since February 20, the increment was equal to 100 - 120 $\sqrt{J}$/day when the strata in the closest roof of the 39th coal seam began to crack, probably as far as the 38th coal seam. Since March 20, the strata as far as the closest roof of the 37th coal seam began to crack and since April, 12, the strata in the higher roof of the 37th coal seam, probably as far as the 36th coal seam, cracked, too. Sporadic events were localized from the roof of the 36th coal seam. Maximum value of the increment of the Benioff's graph reached at the end of June, 1990 the value of 400 $\sqrt{J}$/day.

The third period to November 11, 1990 is characterized by reduction of the increment to the values of 200 - 300 $\sqrt{J}$/day with a negligible falling trend. At this time, the coalface was situated under the first pillar and seismic events were localized by the seimoacoustic method under its second edge.

In the fourth period to April 1, 1991, the expressive change of the character of seismic activity became apparent owing to the coalface drawing-out off the area under the first pillar. Simultaeously, the gradual quiescence of seismic activity was observed under the second edge of the first pillar, as well as revival of seismic activity under the second pillar in the far zone in front of the coalface. The increment of the Benioff's graph moved in the range of 150 - 300 $\sqrt{J}$/day.

The fifth period to October, 1, 1991 brought the total gradual reduction of seismic activity owing to tranquility of the first pillar area. The reduction originated in spite of the fact that the coalface approached to edges of the second pillar and the seismic activity in this region raised. Most of events were seismoacoustically localized to the close roof of the 39th coal seam as far as the 37th coal seam. After the coalface drawing-out off the area under the second pillar at the beginning of September, 1991, the total seismic activity took its quickly decreasing tendence. The increment of the Benioff's graph moved around 110 $\sqrt{J}$/day.

In the sixth period (to November,1991), the weakened zone of the rock mass around the safety pillar became active which culminated by an event of energy of 10^5 J several days after the excavation ending.

The seventh period (since November 25,1991) can be characterized by quick falling of the seismic activity in the whole area surrounding the coalface.

5. CONCLUSIONS

In the paper, the statistical analysis of seismic events, induced during the whole period of excavation of the coalface No.13933 in the 3rd tectonic block at the ČSA Colliery in Karviná, was performed. The results obtained can be summarized as follows:

1. Detection and localization capability of the local seismological network related to the investigated coalface was determined. The network has the detection capability greater than 20 J. The localization capability in horizontal direction is limited by the error of 100 m and in vertical direction by the resolution, if the event originated from the level of excavation or from the higher roof.
2. The close link-up of seismological and seismoacoustic observation was proved. The total energy scale can be divided into three categories:
   - less than 20 J - processing based upon the seismoacoustic data,

- within the interval of 20 J - 100 J - overlap of both methods offering the posiibility of mutual comparison to calibrate the parameters of the algorithm of energy computation
- greater than 100 J - processing based upon the seismological data.

Vertical coordinate of events was calculated from data of the spatial seismoacoustic registration base from the level of excavation up to the height of 100 m.

3. Based upon the analysis of the energy-frequency distribution, significant changes of its slope were found, from the value a=-0.8 for the quiescent state to the value of a=-0.53 during the first six month of excavation. This state can be interpreted as relatively high hazardous for sudden occurrence of a rockburst, because the dangerous states are not indicated by a sufficient number of small events before the proper rockburst.
4. Determination of the third Gumbel's distribution made possible to derive the dependence of the maximum energy E_{MAX} of a single event on the thickness h of the overlying layer situated in the influenced zone of the coalface. The empirical dependence is as follows:
   $\log(E_{MAX}) = 4.0 \log(h)$
   Based upon this formula, the immediate roof of the 39^{th} coal seam, the thickness of which reaches about 30m, is not capable to accumulate the energy greater than 10^6 J, released by a single event. The greatest energies can be accumulated by the thick intact sandstone - conglomerate series of strata in the roof of the 36^{th} coal seam.
5. From the analysis of the the Benioff's graph, the excavation of the coalface can be divided into seven periods, different in their seismic energy radiation. These differences observed can be interpreted as consequence of influence of two residual pillars in the 33^{rd} coal seam, situated in the roof of the excavated coalface.

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