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CORRELATION BETWEEN THE PARAMETERS OF MINING TREMORS FOCAL MECHANISM AND THE SEISMIC HAZARD STATE BASED ON AN EXAMPLE OF THE WUJEK COAL MINE .

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Abstract: Studies on parameters describing the tremor source have been undertaken. These are the angular parameters that determine spatial orientation of the failure plane in source. These parameters were determined from P-wave first motion signs distribution. The parameters that describe the orientation of principal stresses were also calculated. The investigated area included two longwall faces in the Wujek coal mine. It has been found that the parameters describing focal mechanism of tremors are distinctly related to mining and geological conditions of the exploitation and the seismic hazard state resulting from it.

Key words : *mining tremors, fault plane solution, rockburst hazard* .

1. GENERAL INFORMATION

Among the hazards that occur in the hard coal mining industry there there are seismic tremors that accompany mining operations. They are very dangerous both to the underground mining and to the environment at surface in urban areas. At present, in the routine interpretation of mine seismological data the information included in the seismic records is used on a small scale. Epicentral parameters and seismic energy are only determined.

The objective of the carried out studies was to extend the interpretation parameters that describe the tremor source. The assumed procedure for the studies was based on the solutions used during the descriptions of shallow earthquakes.

In the earthquake simulations based on the hypothesis of a failure caused by the action of shear forces a spatial orientation of the failure plane in the source is determined from the far fields records of seismic waves. These methods are named the fault plane solutions.

From the studies on focal mechanism of mining tremors (Gibowicz, 1989; Kusznir, Farmer, 1983; Mc Garr, 1984; Sileny, 1989) it follows that their best equivalent would be a model described by the couple of forces acting in a point source. Then the processes that take place in the source would be the shear processes acting on the rock mass weakness planes.

In the case of this source model a characteristic distribution of P and S body waves radiation of the displacement field of a medium around the source takes place.

The focal mechanism described by the rock mass weakness shear plane model is characterized by the angular parameters that determine the slip type and its direction on the shear plane (see Fig. 1)

The parameters determining the fault plane orientation :

ϕ - strike of fault plane

δ - dip of fault plane

λ - angle of displacement

The parameters determining the P and T principal stresses orientation - azimuth and plunge.

The determination of the above mentioned parameters allows to separate groups of seismic events of different mechanisms and gives information about the direction of forces acting in the source. Next allows to recognize processes that can exert a predominant influence on the generation of mining tremors in a given area of the mined rock mass.

For the work stage that has been completed, owing to the high seismic hazard existing both in the workings and at the surface, the area comprising longwalls No 11b and 12b in seam No 501 of the Wujek coal Mine was chosen.

In a normal procedure the processing of the data separately from each event, takes place. However individual solutions of the parameters of failure planes are in many cases not too certain owing to the small quantity of data (signs of first motion at successive seismic stations), especially, as far as weak tremors are concerned.

In order to solve this problem a statistic method was developed, which for a larger number of tremors, finds a common solution for both the failure nodal planes and the directions of P and T axes. In the cases of the occurence of a larger number of solutions this method allows dividing the events into groups having the same solution. The algorithm is based on the probability model presented by Udias *et al* , 1980 . Two probability computation models were applied to the subject solution. The first one determines the probability of reading the compression from the event *i* at the station *j* by the following equation:

$$\Pi = \gamma + (1 - 2\gamma) \phi (\rho_i A_{ij}) \qquad (1)$$

where :

Π_{ij} - probability of event *i* at station *j*

γ - parameter of reading errors,

ϕ - normalized distribution function,

ρ_i - parameter,

A_{ij} - normalized theoretical amplitude.

The second model includes weights α_j for each station that all the stations record all events

$$\Pi_{ij} = \gamma + (1 - 2\gamma) \phi (\alpha_j \rho_i A_{ij}) \qquad (2)$$

where :

α_j - weights for station *j*

The other notations are the same as in formula (1)

The measure of fitting the observation of event *i* to the common solution is the ratio of consistent or proportion estimators p_i

$$p_i = (1 / I_i) \sum \frac{1}{2} (1 + Y_{ij} \operatorname{sgn} A_{ij}) \qquad (3)$$

where:

Y_{ij} - sign of first motion of the P wave from event *i* at station *j*.

The relationship (3) indicates that the observation of each event is consistent with the common solution. The computation starts from the analysis of the whole group of events for which equal values of the parameter ρ_i are assumed; next, the p_i values are matched in such a way that the events the observations of which fit well to the solution receive high values of p_i, whereas those ill - matched receive low values. Therefore, the observations of the later ones do not influence the common solution.

The criterion for the separation of events in order to create groups is based on the relation between p_i, and this means that threshold value of p and a group made of those events that have the highest p_i values are determined. The threshold value of depends on the data quality and can be changed from 0.8 to 0.4.

2. MINING AND GEOLOGICAL CONDITIONS IN THE INVESTIGATED AREA

The investigated area included two longwalls, 11b and 12b, located in the central part of the Wujek coal mine. The exploitation was conducted in a top slice of the seam No 501 by the longwall with caving mining system. The seam No 501 in the area lies at depths from 640 m to 680 m and reaches about 7 metres in thickness. The exploitation of the longwalls No 11b and 12b started in the southern part of the colliery in the vicinity of the closing goaf runnig along the Klodnicki fault to the main shafts. From the west the longwalls No 11b and 12b border on a goaf area in the seam No 501 worked out by six strike longwalls in two slices. In the east there is a goaf area worked out by five dip longwalls in one slice. The mining and geological situation is shown in Fig.2.

3. CHARACTERISTICS OF THE SEISMICITY

The seismic activity of the studied area longwall 11b and 12b has been inferred from seismological records. A distribution of the parameters of seismic activity is shown in Fig. 3.

For the purpose of obtaining more accurate evaluation of the character of seismic events the location of tremor sources relative to the position of active longwall faces has been also analysed. Most of the events have occured ahead of the longwall faces (long and short panels). The sources of the strongest seismic events were clearly located above the seam No. 416 at a depth of 400-500 m below surface. A sandstone rocks complex about 40 m thick overlying the seam No. 416 could have undergone the process of destruction as a result of underminig.

The longwall face advance rate has significant influence on the seismicity level. Therefore, in order to obtain more fair results in this matter, a normalized parameter E.R.R. (energy release ratio) was determined.

The parameter E.R.R. denotes the relation:

$$ERR = \frac{\Delta E}{\Delta S} \qquad (4)$$

where:

ΔE - total seismic energy as released during the monthly face advenced , J

ΔS - total surface of the roof laid bare by the face advan- during a period of one month , m^2.

The distribution of the E.R.R. parameter values is presented in Fig.3d. The obtained results indicate that the parameter values are visibly differentiated.

The next parameter characterizing the seismicity level and designed for analysis was the recurrence illustrating the empirical relationship between the number of tremors and their magnitude (or energy) according to the Gutenberg- Richter formula:

$$\log N = a - b M \qquad (5)$$

where:

N - number of tremors of magnitudes covering the range $M \pm \Delta M/2$,

a, b - constants.

The parameter "b" was computed by using the maximum likehood method , (Aki, 1965; Utsu, 1965) :

$$b = \frac{\log e}{M - M_{min}} \qquad (6)$$

where:

e - base of natural logarithm,

M - average magnitude of the set of tremors,

M_{min} - threshold magnitude above which all tremors are recorded.

For the computation, tremors of the energy $E > 10^3$ J were taken into consideration and the value of M_{min} was fixed as 0.6. The obtained results are presented in Fig.3e.The changes of the "b" parameter values range from 0.89 to 4.83. The low values of the "b" parameter were associated with the occurrence of strong tremors of the energy 10^5 J and 10^6J.

4. ANALYSIS OF THE RESULTS

The obtained data as being the set of information on the P waves first motion signs for all mining tremors recorded by the mine seismological network were subjected to the analysis.

The first one consisted of the separate calculation of angular parameters of source failure plane orientation for each event, whereas the second one consisted of the application of a method for group separation of parameters of tremor source mechanism.

In the first case the angles ϕ , δ , λ were calculated, and their distribution depending on

- seismic energy of tremors,
- location of tremor sources with respect to longwall face,
- time of mining,

was analysed.

The classification of the tremor source failure plane orientation was executed - table I.

Table I. Types of focal mechanisms separated from the spatial orientation of the tremor source failure plane.

No	Type of mechanism	Symbol	δ^o	λ^o
1.	Normal - dip slip	ND	>90	60-120
2.	Normal - strike slip	NS	>90	0-30 or 150-180
3.	Normal - mixed slip	NC	>90	30-60 or 120-150
4.	Reverse - dip slip	RD	<90	60-120
5.	Reverse - strike slip	RS	<90	0-30 or 150-180
6.	Reverse - mixed slip	RC	<90	30-60 or 120-15

The dependence of the solution of the failure plane parameters described by angles δ and λ on the seismic energy of tremors is presented in Fig.4. It follows that for an energy class of 10^3 - 10^4J a reverse fault type of focal mechanism (R) is prevalent, whereas for tremors of the energy higher than 10^5J a normal fault type of focal mechanism prevails but with the slip domination in the strike direction. The results of the correlation between the types of focal mechanism of tremors and their source location with respect to the longwall faces 11b and 12b are shown in Fig.5. It is evident that the normal type events (N) mostly occur in the nearby goaf, while the reverse type events (R) occur in the panel ahead of the longwall faces. The third factor in relation to which the obtained set of parameters of the solution of the tremor focal mechanism was analysed was the time of mining. It is assumed that this factor reflects local mining and geological conditions and the associated stress field which forms the

seismic regime in the studied rock mass area.
The data shown respectively in Fig. 6 are visibly differentiated. To quantitatively characterize changes in each type of mechanism of tremors a distribution of the ratio of the number of N type events to the number of R type events was calculated. This ratio normalizes the measurement material as far as the seismic activity is concerned (see Fig. 6c).
To find a predominant azimuth direction of the determined disruption planes and directions of the P and T principal stress axes a method for common statistic determination of disruption planes parameters was used.
The analysis allowed the separation of 3 groups of tremors with the same mechanism parameters, that is the predominant azimuth of disruption planes and the azimuth of the P and T principal stress axes.
The first distinguished model of the focal mechanism of tremors is the dip-slip reverse model. The P and T principal stresses lie, here, in a vertical plane. The dip of the action plane is, exactly, 90°. In this model, horizontally acting shear stresses (P axis) and vertically acting tensile stresses (T axis) occur.
The second distinguished model of the focal mechanism of tremors is the slip model but with a clear domination of the horizontal component (strike-slip). The principal stresses in the model lie on the inclined plane and the dip of the action plane is, here, about 40°. The third distinguished model of the focal mechanism of tremors is the dip-slip normal. The P and T stresses act in a vertical plane with a dip of 90°. The P shear stress is vertical and the T tensile stress is horizontal.

The three basis models of the sources of mining tremors associated with the 11b and 12b longwall mining have been correlated with the local mining and geological conditions and the parameters of seismic activity.
Six characteristic mining periods constituting the correlation basis could be distinguished in Fig. 6.

The first period comprising July and August, 1990 is the beginning of mining of the 11b longwall panel. A small number of tremors with low average energy and low total energy occured during that time. The "b" parameter value was high. The tremors that occurred were localized mainly far ahead of the longwall face and they were weak, of the energy ranging between 10^{3}J and 10^{4}J. The period, in general, was characterized by a low seismic hazard. The predominant type of mechanism of tremors, at that time, was the dip-slip-reverse type. The distribution of the ratio of the number of the N type tremors to the number of the R type tremors was high at that time. The obtained azimuths of the slip planes are perpendicular to the faults existing in this area.

In the second period covered September and October ,1990, the 11b longwall face was passing under the recovered coal seam No. 416, whereas the 12b longwall was mined under the main drifts protecting pillar body. The ground movement fronts were then shifted and their alignment took place in November, 1990. The analysis of seismicity showed a high seismic hazard. A large number of tremors of the energy lower than 10^5J have occurred and also strong tremors with the energy of 10^5 and 10^6J were recorded. The parameter values of the average energy and the total energy were high. The "b" coeffcient value considerably dropped at that time, which is an evidence of the large increase in seismic hazard.
The value of the quotient N/R significantly dropped in September, 1990. The predominant type of tremor mechanism, at that time, was the strike-slip type. The tremors of that type of mechanism were mainly localized under the unmined part of the seam No. 416 . In the model, a domination of displacements in sources in the horizontal direction becomes pronounced. The azimuth of one of the nodal planes could be correlated with the working face line. It has been found that it is parallel to the 11b and 12b longwall faces.

The third period was distinguished in November and December, 1990. The 11b and 12b longwall faces were driven evenly. The 11b longwall was under the extracted seam No.416, and the 12b longwall was under the coal body of the seam No.416. In November a large number of tremors is visible with high both average energy and the total energy, and a high value of the "E.R.R." parameter can be found. The lowest value of the "b" coefficient also occured at that time. The tremors were mainly localized in the nearby goaves and not far away ahead of the longwall face. Most of the high energy tremors - two of an energy 10^6J and six of an energy of 10^5J - occurred in November. The N/R ratio slightly increased in November, then in the next month it dropped again. The tremors from that period of time are mainly characterized by the strike-slip type mechanism with a significant displacement in the source in the horizontal direction, and their sources are mostly located under the unmined part of the seam No.416.

The next, fourth period includes January and February, 1991. The ground movement fronts of both of the longwalls moved parallel to each other, but the 11b longwall was being already driven under the unmined part of the seam No.416, and the 12b longwall was, at first, being driven under the extracted part of the seam, but during the second half of February it was approaching the edge of the seam No.416 and entering the area underlying the coal body of the seam. The number of tremors remained at a level comparable with the earlier period and both the average energy and the total energy slightly increased. The "E.R.R." coefficient values were low in that period and the "b" coefficient values considerably dropped in January. This drop is an evidence of the increase of seismic hazard, which was confirmed by a tremor of the energy 10^6J that occured on 30th January. In the beginning of January the value of the N/R coefficient remained low. The sources of a certain number of tremors were localized close ahead to the face and far ahead of the face in a zone being under the influence of edges in the seam No. 416. The others were localized in goaves. In the zone being under the influence of edges occuring in the seam No.416 dominates the dip-slip-reverse type mechanism of tremors.

The fifth period includes the months March, April, May and June 1991. Both of the longwalls were mined, at that time, under the unmined part of the seam No. 416. The largest number of tremors from the whole of the past mining period occurred in March. The average energy remained, initially, at such a level as before, but in April, however, it significantly dropped. The values of the total energy and the E.R.R. parameter increased in March and decreased in the months that followed. The values of the "b" coefficient and the N/R quotient dropped in the beginning of the period, later, however, showed an upward trend. The tremors of the strike-slip type mechanism, that is those with the horizontal displacement in a source, were predominant at that time. They occurred, first of all, in the area of the unmined part of the seam No.416. The mechanism of this type of tremors was the same as in the second distinguished period of mining of the analysed longwalls.

The sixth distinguished period, as the last one, includes the months from July, 1991 to the end of the analysed period. During the second half of July the longwalls 11b and 12b had approached the edge in the seam No.416 and, next, they passed under the extracted parts of the seam No.416 and under the narrow pillar protecting the mine drifts. In general, the number of tremors dropped during that period. The value of the average energy in July remained at the same level as before and in August it grew higher. This drop in a number of tremors is indicative of the seismic hazard characterized by the occurrence of tremors of higher energies. The total energy and the E.R.R. coefficient show an upward trend in the end of the analysed period. In July the values of both the "b" coefficient and the N/R quotient dropped. That period was surely characterized by the focal mechanism other than those analysed before. That was the dip-slip normal solution for nodal planes. Azimuths of disruption planes are almost parallel to the edges. The location of strong tremors from that period is shown in Fig. 2.

5. CONCLUSIONS

1. In accordance with the analysis presented analysis the new seismological parameters could be introduced into the mining seismology. These parameters yield information on the focal mechanism and, at the present development stage of mining seismology, seem to be the most useful and latest data in the field of expanding the state of knowledge of the processes taking place in the source of tremor. The angles ϕ, δ and λ, that describe the spatial orientation of the failure plane, yield information on the direction of the forces action in the source of a tremor, which allows us to identify the processes that can exert a decisive influence on the generation of tremors.

2. Very keen analysis of the seismic events from the Wujek coal mine, as far as the seismic hazard is concerned, and the recognition of their mechanism have yielded new information on the character of these events. Three main groups of seismic events of different mechanisms have been obtained.

3 A group of the dip-slip-reverse type tremors mainly occurred under the extracted part of the seam No. 416 during the initial mining period.

4. The next, largest group of tremors was characterized by the strike-slip model, that is the shear type mechanism with displacements dominating in the horizontal direction. This group of tremors mainly occurred in the area of unmined part of the seam No. 416. The geomechanical interpretation of these results would look as if the destruction process in a tremor source were of the character of the phenomenon of delamination of the strong roof strata complex, overlying the seam No. 416.

5. The last distinguished group of tremors was characterized by the dip-slip-normal type mechanism. The tremors, mainly occurred when the longwall mining operations were conducted under the main drifts

protecting pillar. This type of tremors could likely be connected to the failures with approximate vertical orientation. As regards the energy, the tremors of this source model were, here, the strongest, of the order 10^5 and 10^6J.

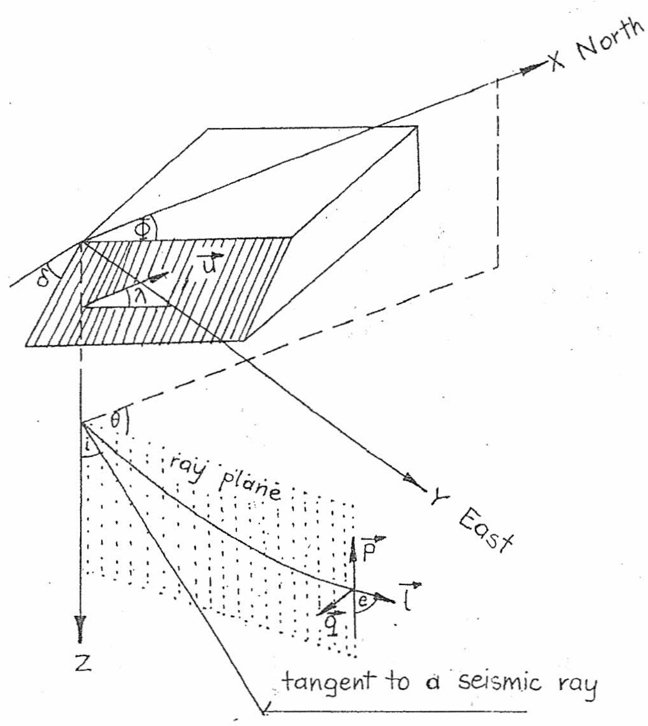

Fig. 1. A diagram for the seismic source-receiver point system (after Aki, Richards, 1980)

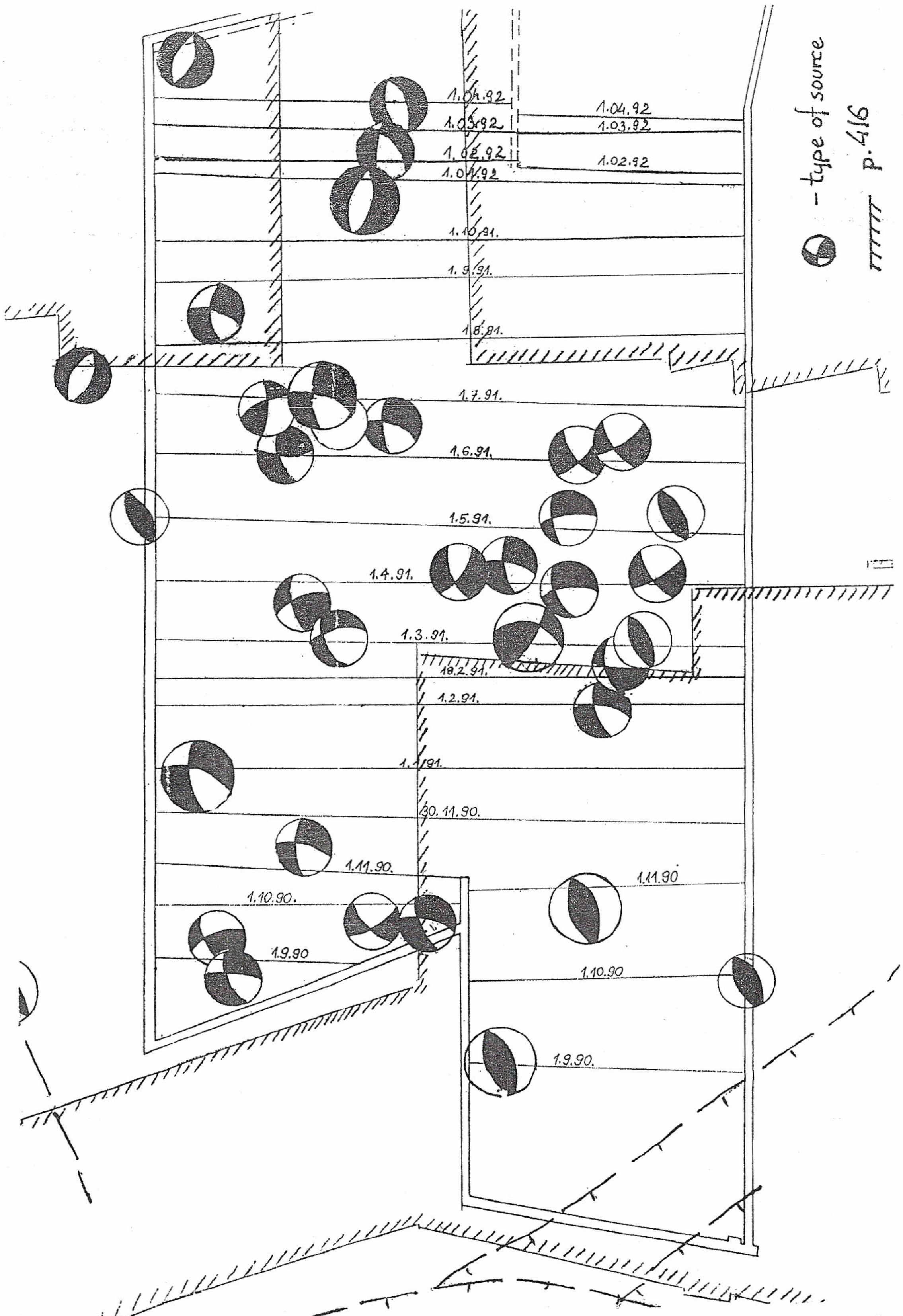

Fig. 2. Area of investigations - longwalls No 11b and 12b in the Wujek coal mine. Focal mechanisms of the strongest tremors are shown

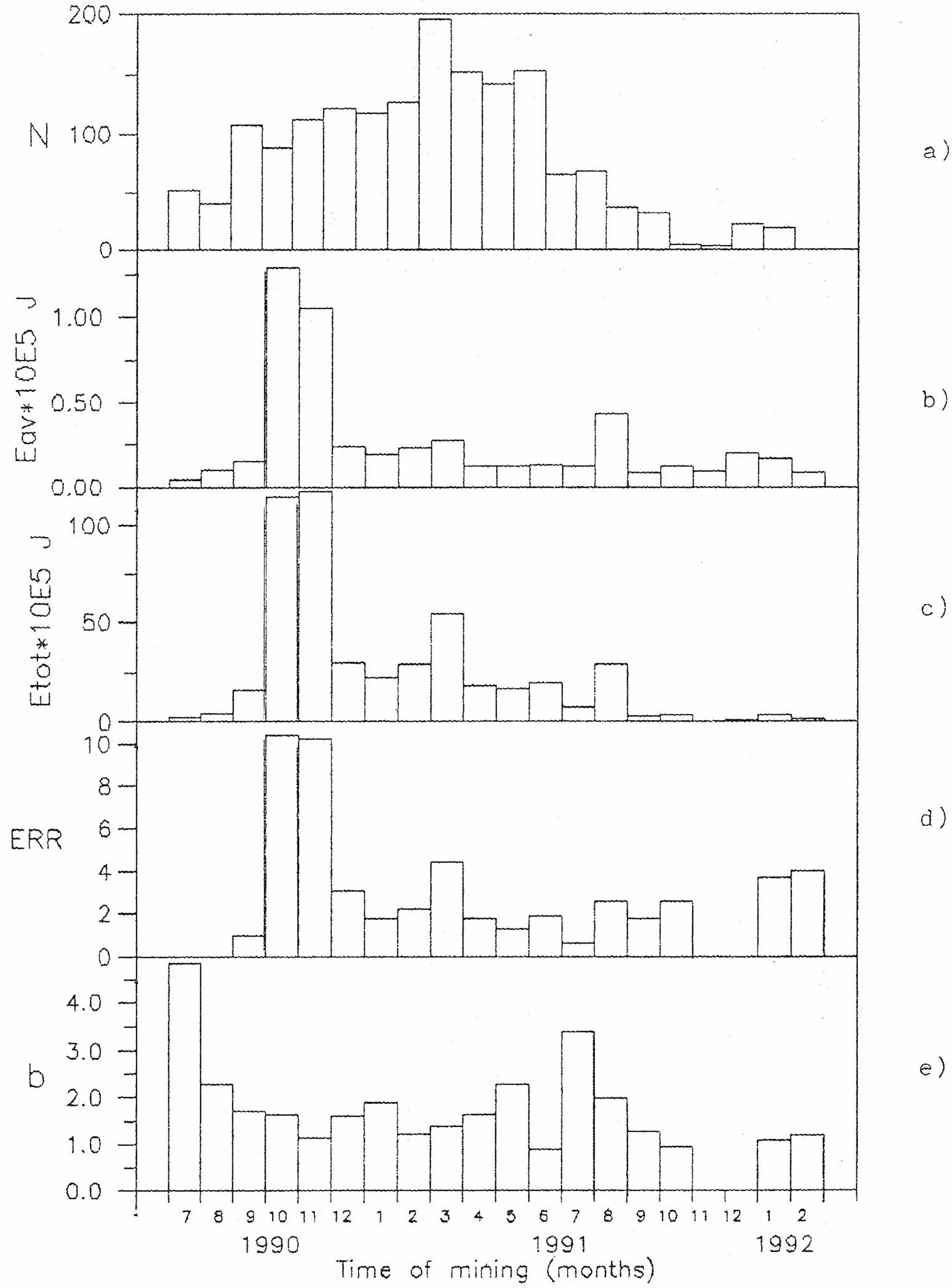

Fig. 3. Parameters of seismic activity during the exploitation of longwalls no 11b and 12b. a - number of tremors; b - average energy of tremor c - total monthly seismic energy; d - E.R.R. - energy relase ratio; e - b parameter of Gutenberg-Richter formula

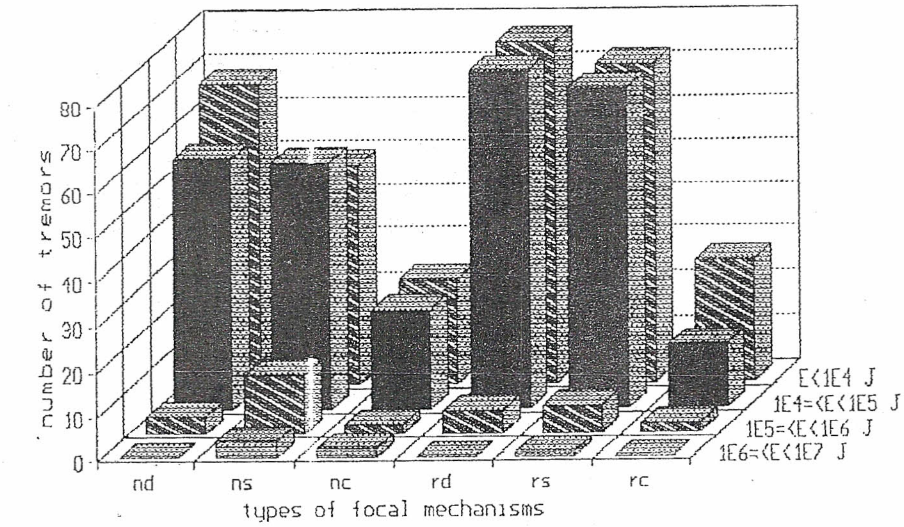

Fig. 4. Distrubution of types of focal mechanisms of mining tremors in respect to their seismic energy

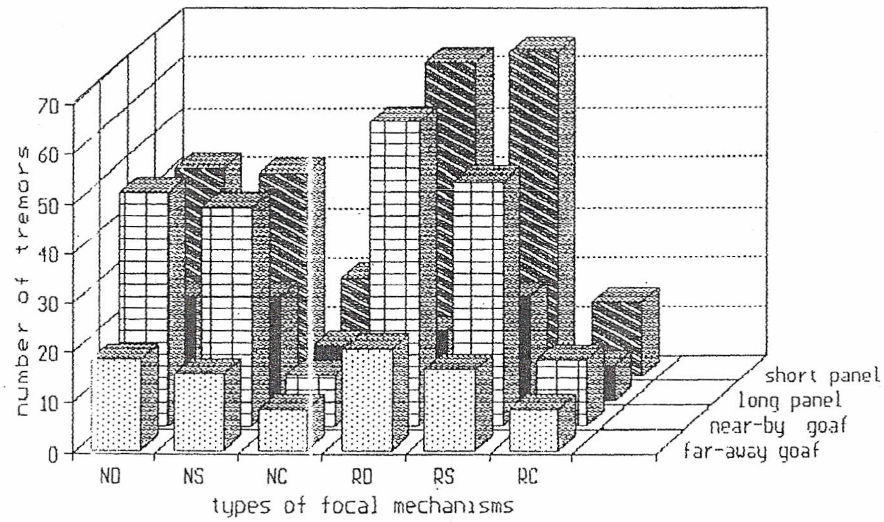

Fig. 5. Distribution of focal mechanisms of mining tremors in respect to their postitions to the longface

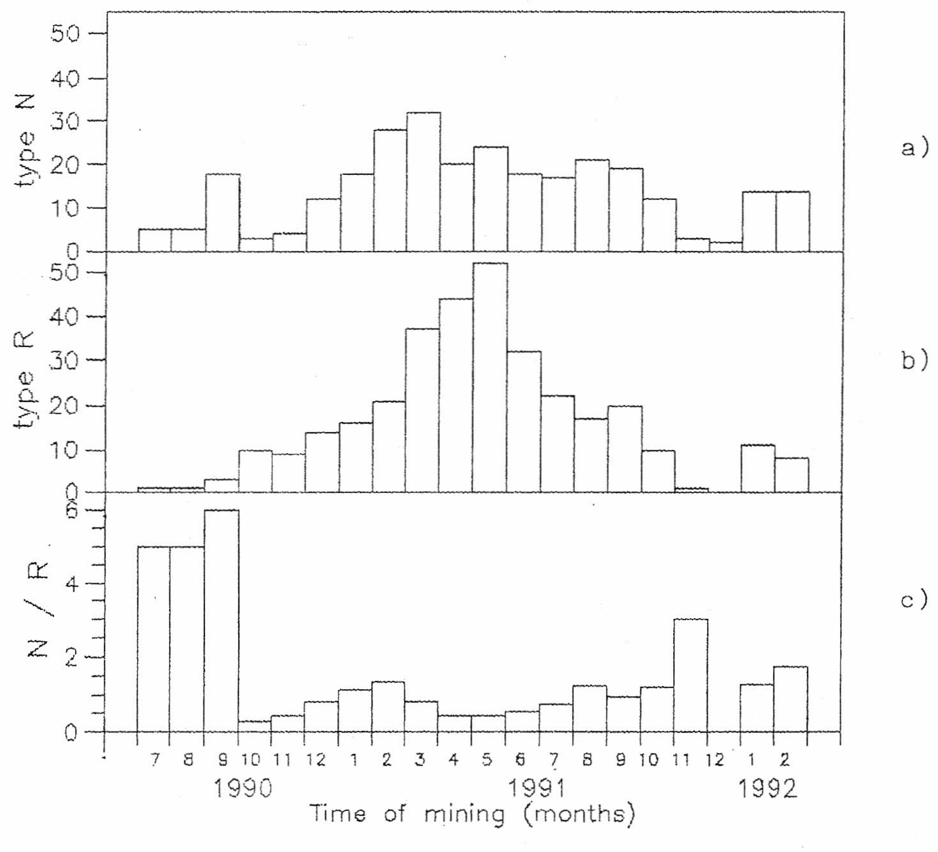

Fig. 6. Distribution of types of focal mechanism versus time of mining. a - number of tremors with normal N type of mechanism b - number of tremors with reverse R type of mechanism; c - ratio of N to R

REFERENCES

Aki, K. (1967). Scaling law of seismic spectrum, *J.Geophys Res.*, 72,1217 -1231

Aki, K., P.G. Richards (1980). *Quantitative seismology,* Vol. I, II, ed. W.H. Freeman and Company, San Francisco , 934 pp.

Dubinski, J. and Z.Wierzchowska (1973). Methods for calculation of energy of mining tremors in Upper Silesia, *Komunikat GIG,* 591

Gibowicz, S.J.(1985). Seismic moment and seismic energy of mining tremors in the Lubin copper basin in Poland, *Acta Geophys. Pol.*,**33**, 243-257.

Gibowicz, S.J.(1989). Mechanism of mining tremors, *Publs. Inst.Geophys. Pol. Acad. Sc.*, M-13.

Goszcz, A. (1991). Roof rockbursts and ways to combat them, *Archiwum Górnictwa.*

Kasahara, K. (1981). *Earthquake mechanism,* Cambridge University Press, London.

Kidybinski, A. (1982). *Principles of mining geotechnics*, Katowice, ed.Śląsk (in Polish).

Kusznir, N.J. and I.W.Farmer (1983). Rockburst phenomena in British coal mines, in: *Rockburst:prediction and control*, Symp. Proc., London. 1983.

McGarr, A. (1984). Some applications of seismic source mechanism studies to assessing underground hazard, in: *Rockburst and Seismicity in Mines*, South African Inst. Min. Metal., Symp. **6**, 199-208.

McGarr, A., S.M. Spottiswoode and N.C. Gay (1979). Observations relevant to seismic driving stress, stress drop, and efficiency, *J.Geophys.Res.*, **84**, 2251-2261.

Sileny, J., A.R. Ritsema , I. Csikis and J. Kozak J. (1986). Do some earthquakes have a tensile source component? in: *Physics of Fracturing and Seismic Energy Release, PAGEOPH,* **124**.

Sileny, J. (1989). Mechanism of weak mining tremors by amplitude inversion, in: *Seismicity in Mines, PAGEOPH,* **129**.

Udias, A., E. Buforn , D. Brillinger and B. Bolt (1980). Joint statistical determination of fault plane parameters, *Bull. Seism. Soc. Am.*, **70**, 149-170.