MEASUREMENT AND ANALYSIS OF SEISMIC EVENTS IN DEEP-LEVEL COAL MINE

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ABSTRACT

A field investigation by making use of the seismic method has been carried out in order to comprehend the mechanism of rockburst and gas outburst and their predictive measures. The seismometers were so arranged both on the surface and underground as to enclose a mining panel. Seismic signals detected by the array were recorded and processed by the 32-kwords computer system. At present the system is available for analysing the source location and Richter's scale of each event and for visualizing the distribution of seismic foci and released energy at any mining stage.

The magnitude distribution of events can be regarded as a comparable index of the seismic activities among mining panels. An analysis of the spatial density distribution of seismic energy in the mining panel can be useful to distinguish a highly stressed zone from stress released areas. The energy released curve or the rate of energy release determined from seismic data is also a good indication of the seismicity.

In this paper the results of the observation in Sunagawa Coal Mine will be presented and a discussion will be focussed on the prediction of seismic activity in a given mining panel.

INTRODUCTION

In the last two decades the annual rate of increase in depth of Japanese coal mines has been 12m/year so that the mean depth reached 571m below the surface in 1979. The incidence of rockburst and gas outburst has gradually increased with mining depth, which has resulted not only in fatal accidents, but also frequent disasters involving explosions and underground fires. According to the statistics surveyed by the government the incidences of rockbursts have amounted to 11 since 1960 and by them 22 miners were killed and 34 were injured. Also the outburst occurred at Horonai Coal Mine in 1977 and interrupted the production for 23 months so that the annual product fell abruptly from 1.4 million tons to zero. Thus a solution for predicting rockburst and gas outburst is essential to the safety and productivity in the deep-level coal mines.

With this point in view, in-situ measurements using seismic method have been carried out since 1970 in order to comprehend the causation of rockburst and gas outburst and to find associated precursive phenomena. The field investigation was partly motivated by the incidence of rockbursts at Bibai Coal Mine in 1968 at which small scale earthquakes were recorded by the standard seismograph stations

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of Japan Meterological Agency at the distances 50 to 100km from Bibai City. This fact suggested that rockburst and gas outburst might be one of seismic events similar to earthquake and that they might be so distinctly detected by seismometers which arrayed close to a mining panel that one could determine seismic focus as well as seismic energy. The investigation was also based on the fact that miners had frequently heard audible noises which were emitted from rock around underground openings just before the occurrence of rockburst and gas outburst so that it might be possible to predict them by monitoring the seismicity in the mining panel. The measuring system with 32-kwords mini-computer has been developed and applied to Sunagawa Coal Mine since 1976. The system is not only capable of recording automatically seismic event whose magnitude exceeds a prescribed threshold, but also available for analysing the source location and Richter's scale of each seismic event and for visualizing the distribution of seismic foci and released energy at any mining stages.

In this paper the prediction of rockburst and gas outburst will be discussed by exemplifying the seismic data obtained at Sunagawa Coal Mine. Before going into the main argument the terminology appearing in this text should be described briefly for avoiding unnecessary confusion. In this paper seismic event stands for rockburst or gas outburst. The seismic method can not distinguish gas outburst from rockburst by itself, but can only detect both of them as seismic event occurred at underground. Generally speaking the seismic event which takes place at coal seam and results in expulsion of coal fragments with gases can be regarded as gas outburst. Also in this paper the prediction is considered in two ways; one is the prediction of seismic activity in a given mining panel which may be represented by the greatest magnitude of event and seismic energy released by extraction of a unit area of coal seam, and the other is the prediction of impending rock or coal failure whose scale exceeds a prescribed level.

In the following text these problems will be detailed.

MEASURING METHOD

Because the measuring system has already been described in a previous paper, Isobe et al (1979), only the block diagram of the overall system is shown in Fig.1.

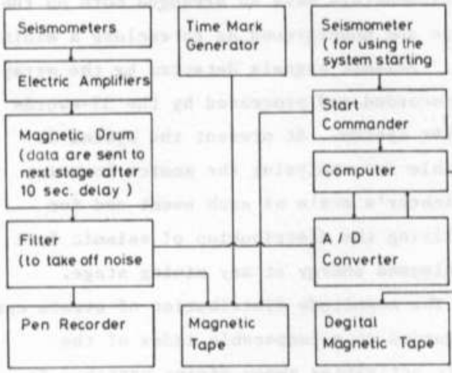

Fig.1 - Blockdiagram of measuring system

The seismometer is capable of detecting the vertical component of the ground movement with sensitivity of 2.5 volts per the velocity of 1cm/sec. The seismic array consists of more than four seismometers to be able to determine the source location of seismic event. The signals transduced by seismometers are processed by electronic equipment and recorded on an oscillograph regardless of their amplitudes. When the amplitude of signal exceeds a prescribed threshold, signals are recorded on digital magnetic tape at the rate of 400 words a second. The recorded seismic data are processed by the computer programs to determine the source location and to evaluate Richter's

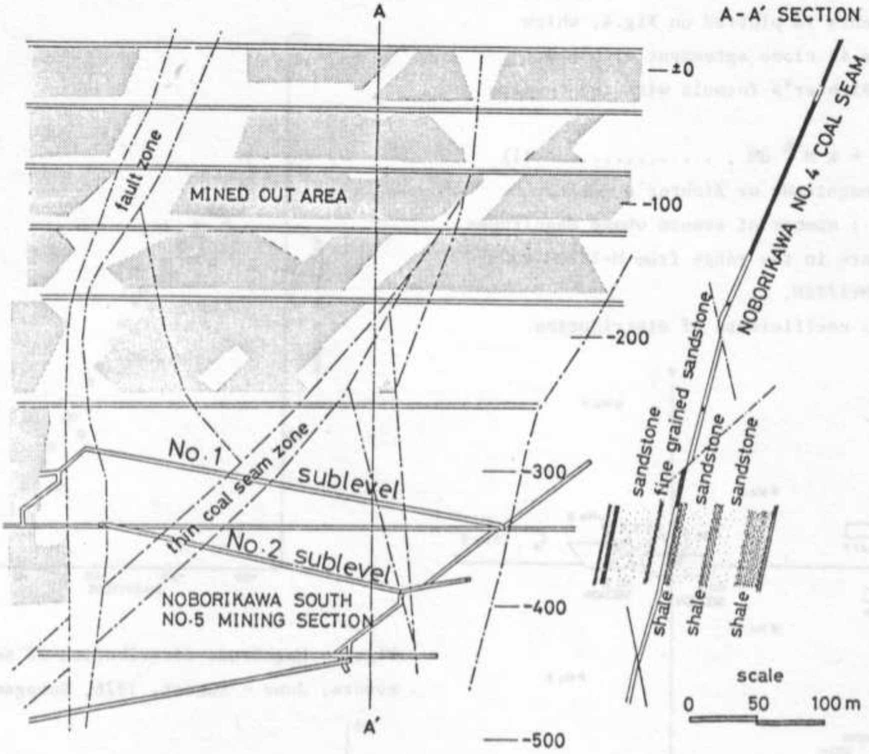

Fig.2 - Mine layout and geological features at the mining panel to which the seismic method was applied.

scale and seismic energy, then reduced data are compiled on auxiliary storage of the computer. The iterative least squares method is used to calculate the hypo-center of seismic event, and the Muramatsu's formula and the Gutenberg-Richter's formula in seismology are adopted to evaluate the Richter's scale or the magnitude, and the seismic energy respectively.

The layout of the mining panel to which the seismic method was applied is illustrated in Fig.2. The strata were steeply inclined by 70 degrees in the panel, and the coal seam with 3m thickness was covered with massive sandstone and directly underlain by the alternation of various grained sandstone strata. The monitoring system consisted of eight seismometers as shown in Fig.3. Six of them were placed on the surface and the others were installed at the underground roadway which was situated at 800m below the surface. No.1 to 6 seismometers were placed on the surface, and No.7 and 8 were installed at the underground roadway. Symbols A, B and C denote shot-firing points used to determine the P-wave velocities.

MAGNITUDE DISTRIBUTION AND SEISMIC ENERGY

No sooner the extraction was commenced at the mining panel, than a number of seismic events were monitored by the system, so that the number of events which were recorded on an oscillograph had amounted to 5,790 in the period during which two sub-levels had been mined out. The magnitude distribution of the seismic events is plotted on Fig.4, which seems to be in close agreement with the Gutenberg-Richter's formula with the b-value of 0.69:

$$N\,dM = k\,M^{-b}\,dM \;,\; \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where M : magnitude or Richter's scale,

N dM : number of events whose magnitudes are in the range from M-1/2dM to M+1/2dM,

k,b : coefficients of distribution.

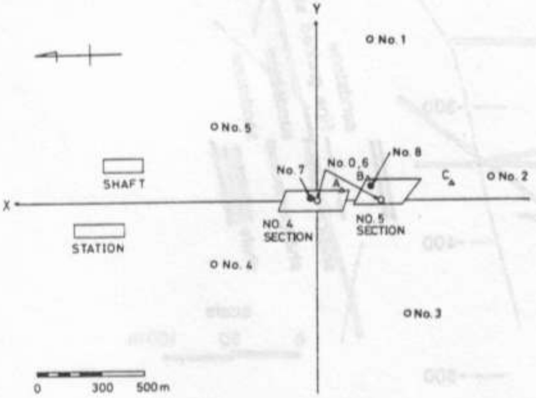

Fig.3 - Seismic array applied to Sunagawa Coal Mine, 1976.

The seismic energy released in the period is indicated in Fig.5. In this diagram a daily seismic energy is in turn added to the cumulative energy released from the day since the mining started. It should be noticed that the cumulative energy increased with enlargement of the mined out area, although daily seismic energy varied day by day so that several jumps appeared in the piece-wise linear curve in Fig.5. If the release rate of seismic energy or the spatial rate of energy released is defined as the seismic energy released by unit area extraction of coal seam, Cook (1976), the mean rate of energy release in the mining panel is estimated by 10.5 J/m^2.

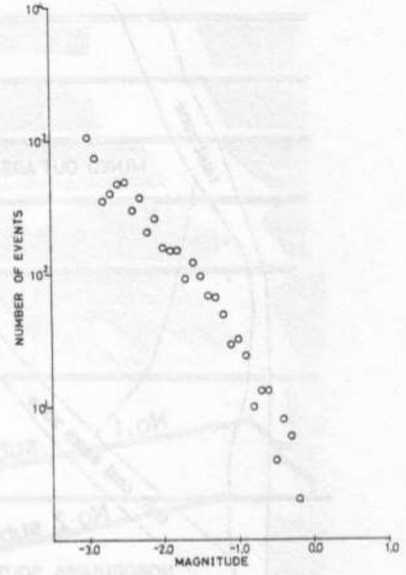

Fig.4 - Magnitude distribution of seismic events, June - August, 1976, Sunagawa Coal Mine

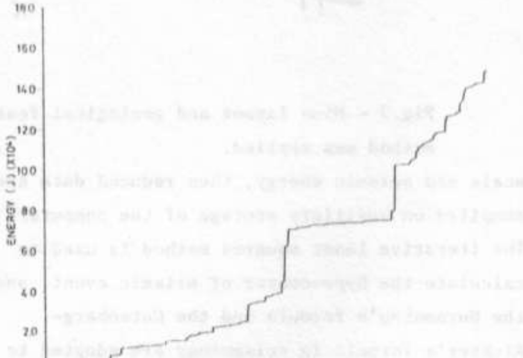

Fig.5 - Seismic energy released with proceeding of mining, June - August, 1976, Sunagawa Coal Mine.

Thus the observation over three months revealed that the seismicity induced by extraction of coal seam might be followed by the Gutenberg-Richter's formula and that the seismic energy might be in proportion to mining area.

Now let us consider on the prediction of the greatest magnitude among seismic events which may happen until the mining in a given panel comes to the end. The b-value determined from the magnitude distribution converged gradually to a constant value with increase of mining area as shown in Fig.6. The b-value on a certain day in Fig.6 was determined from all the seismic events occurred the day after the mining of the panel has started. From the diagram it seems to be that the b-value which stands for the seismicity in the mining panel may be determined with sufficient accuracy from seismic data over 20 days. The seismic energy release rate was estimated by the quotient of cumulative energy and total mining area as plotted on Fig.7. The rate showed a step-wise increase with the progress of mining. However, the first plateau of the curve was realized after about 20 days from the start of mining.

Once the b-value and the seismic energy release rate are determined, the greatest magnitude of seismic event, which will occur in the whole period, may be predicted by the following equation:

$$\overset{M_L}{\underset{M_S}{}} E_s \, N \, dM = G \, A \, , \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

where M_S : the lowest magnitude which can be detected by the measuring system,

M_L : the greatest magnitude to be predicted,

G : the seismic energy release rate,

A : the area to be mined out in the whole period,

E_s : the seismic energy of event whose magnitude is M,

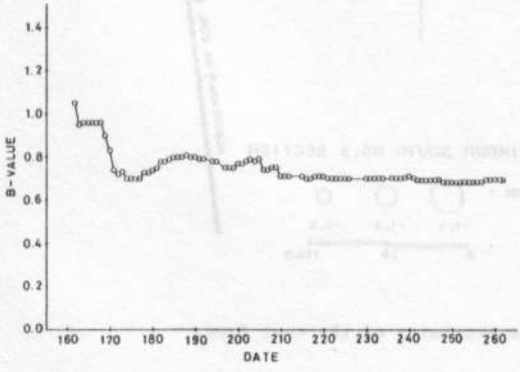

Fig.6 - Change of the b-value.

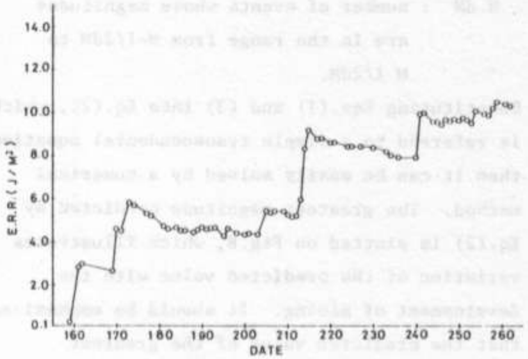

Fig.7 - Change of the seismic energy release rate.

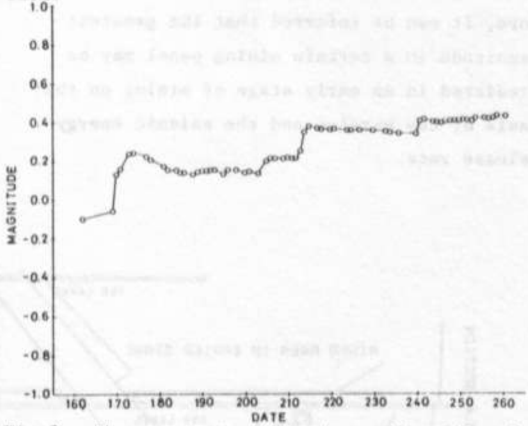

Fig.8 - The greatest magnitude predicted by the b-value and the seismic energy release rate.

$$\log_{10} E_s = 11.8 + 1.5\,M\ , \ \ldots\ldots\ldots \quad (3)$$

N dM : number of events whose magnitudes are in the range from M-1/2dM to M 1/2dM.

Substituting Eqs.(1) and (3) into Eq.(2), which is referred to a simple transcendental equation, then it can be easily solved by a numerical method. The greatest magnitude predicted by Eq.(2) is plotted on Fig.8, which illustrates variation of the predicted value with the development of mining. It should be emphasized that the predicted value of the greatest magnitude converged to a constant value with the mining time lapse. At the present, therefore, it can be inferred that the greatest magnitude in a certain mining panel may be predicted in an early stage of mining on the basis of the b-value and the seismic energy release rate.

SOURCE LOCATIONS OF SEISMIC EVENTS

In the same period as described in the preceding passage 360 of seismic events had their foci located; most of them crowded in the proximity of the advancing coal face from about 30m ahead and 30m behind of it. The coal pillars which had been left in the panel were also affected by a large number of seismic events. Fig.9 illustrates an example of the seismic events whose sources were located in the front abutment of the advancing coal face. In this figure a seismic event is represented by a circle whose center and radius correspond to the epicenter and the magnitude respectively, and the mined out region is delineated by a set of polygons. Fig.10 shows the spatial distribution of seismic energy around coal face, which was drawn by the following procedure:

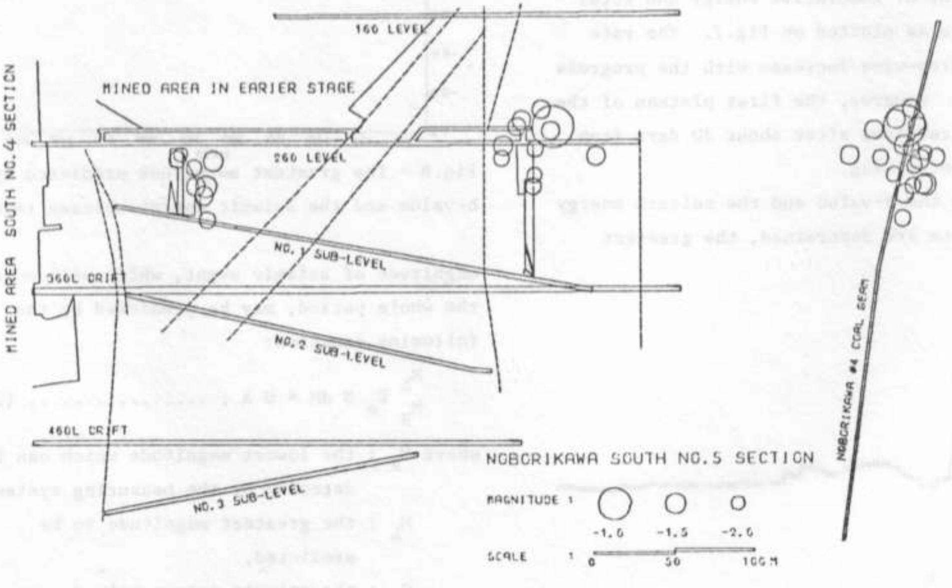

Fig.9 - Seismic foci where were located in the proximity of the coal face.

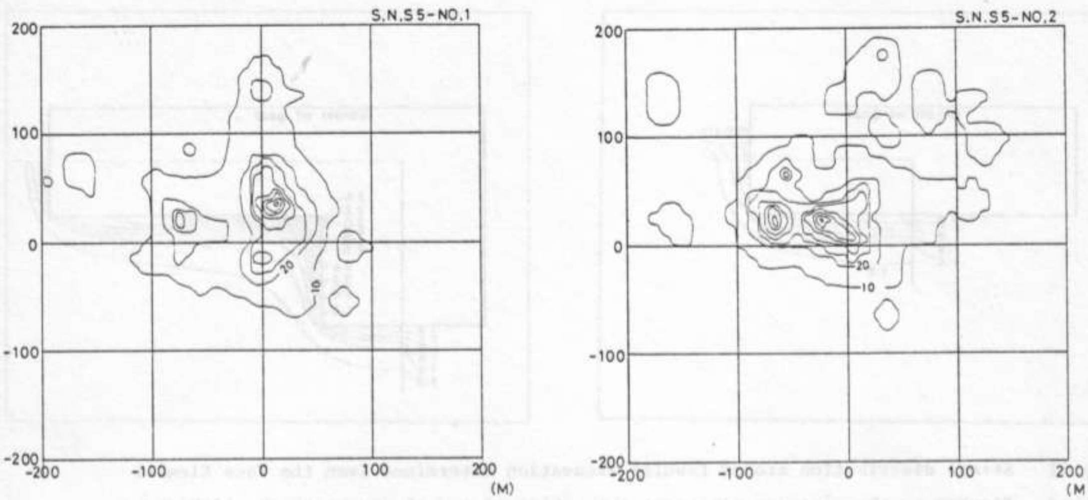

Fig.10 - Spatial density distribution of seismic energy. The origin coincides with the centroid of mining block in each day. The positive direction points towards the front abutment of coal face. The increment of contours corresponds to J/m^2.

At first, the daily spatial distribution of seismic energy was calculated and represented in the local co-ordinates system whose origin coincided with the centroid of the mining block in the day.

Then, these results for the mining period in each sub-level were superposed on the reference frame to obtain the distribution around the coal face.

Finally, the synthesized distribution of energy was smoothed by a trend analysis, that is the seismic energy E_i at i-th mesh was transformed from the synthesized distribution of energy E_j, $j=1,2,\ldots,n$, by the relation of

$$E^*_i = \sum_{j=1}^{n} \frac{E_j}{(a^k + d_{ij}{}^k)} \Big/ \sum_{j=1}^{n} \frac{1}{(a^k + d_{ij}{}^k)} \quad \ldots\ldots\ldots\ldots\ldots (4)$$

where d_{ij} : the dimensionless distance between i-th mesh and j-th mesh,

a : a constant, say unity,

k : a power, say 1 to 5.

It is noteworthy that the proximity of the advancing face was enclosed by higher energy contours than solid coal or caved region some distance from the face. The results obtained from the observation, above mentioned, may be explained by a stress analysis around the mined out region. Fig.11 indicates the stress distribution around a tabular excavation using the Face Element Method, Crouch and Fairhurst (1973). In the figure the stress which is applied just ahead of coal face is raised up to 2.0 times higher than the lithostatic pressure under the situation such as No.1 sub-level. For the configuration shown at No.2 sub-level the stress at the apex of ribside and face is intensified more than that of the former case. The region where the higher stress concentrates can, therefore, be regarded as a potentially dangerous zone at which seismic events may take place. Although the number and gross energy of seismic events, in the vicinity of the face, have much scattered values from place to place, the attention should be paid to the coal face from the view point of predicting seismic events.

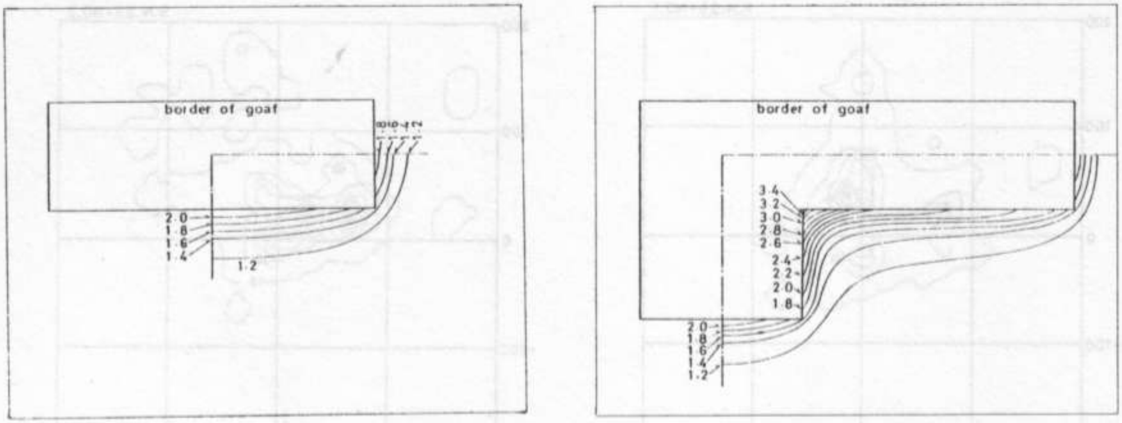

Fig.11 - Stress distribution around tabular excavation determined from the Face Element Method. Figures on the contours represent the ratios of normal stress to the lithostatic pressure.

Fig.12 illustrates seismic events which radiated from the coal pillar left in the mined out region. The incidence of these events suggests that the pillar might have been destroyed by the stress beyond its load-bearing capability. Therefore, it is conjectured that solid coal pillar should have seismic event proneness when the coal face proceeds towards it. The condition that the coal pillar is sound or has yielded may be estimated from the history of the seismicity, because a pillar may be referred to as sound state unless seismic events have been emitted from it. Thus, it has been confirmed that the seismic method is one of the most useful tools to survey the state of coal pillars.

MAGNITUDE OF IMPENDING SEISMIC EVENT

Now the discussion will be focussed on the prediction of the magnitude of seismic events which are generated in the vicinity of the coal face or solid coal pillar left in mining region, because both of them were realized as potentially dangerous zones for impending failure as described previously. Before going into detail, sequential seismic events whose sources were located in coal face or coal pillar should be analysed with respect to time and magnitude.

Fig.13 represents the time sequences of seismic events whose foci were shown in Figs. 9 and 12. Though these many events took place in rather short time, total seismic energy was not released by a few main events, but was divided into small fractions of a number of events. The magnitude distribution of these sequential events is plotted on Fig.14. It should be noticed that the distribution seems to be in close agreement with the Gutenberg-Richter's formula, even if these events occurred in shorter time than that taken in Fig.4.

For predicting the magnitude of impending failure in the proximity of coal face or solid pillar, the behaviour of sequential seismic events suggests the same procedure as that adopted to the prediction of the greatest magnitude in the mining panel. When the coal face is regarded as source of impending failure, the seismic energy to be released within a day can be estimated as the product of the seismic energy release rate and the area to be mined on the day. So the maximum magnitude can be

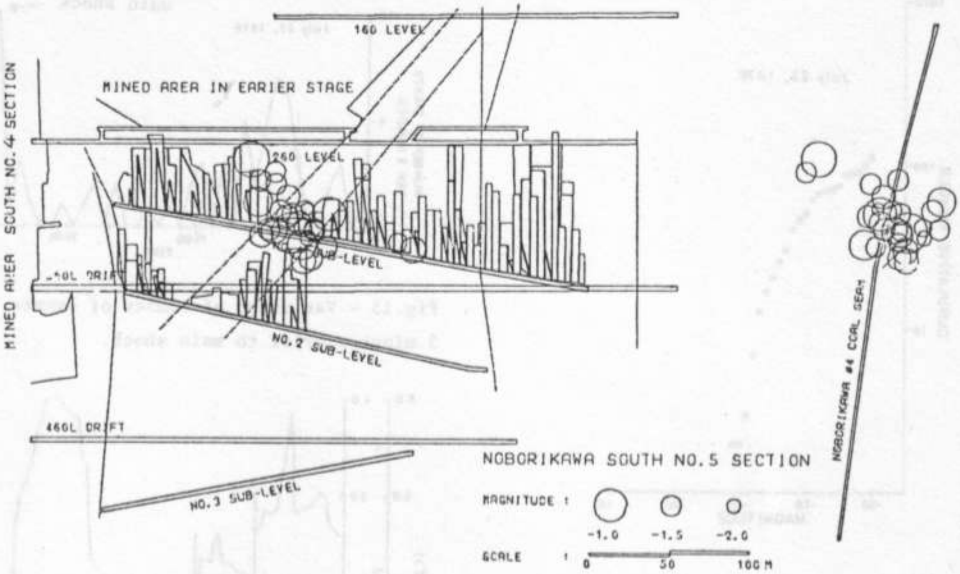

Fig. 12 - Seismic foci which were located in the coal pillar.

calculated by Eq. (2). The b-value to be applied to the equation should be chosen as the minimum value among those determined from daily seismic data. If a coal pillar is assumed to be dangerous, the seismic energy accompanied by failure of the pillar should be estimated from the cross-sectional area of the pillar. The procedure of the prediction of the greatest magnitude is similar to that previously described.

TIME SEQUENCES OF SEISMIC EVENT

The time sequences of seismicity were also analysed to examine whether precursive phenomena prior to impending failure were realized or not. Now it will be described the results obtained from seismic events whose magnitude were greater than -0.5. Two measures were taken as the most probable indices of the time sequences. One is the number of events within a unit time, which has been called simply "count rate" or "event rate" in the field of acoustic emission and is regarded as a promising measure of precursive phenomena, Stebley and Leighton (1977), Brady and Leighton (1977) and Watanabe and Nakajima (1979). The

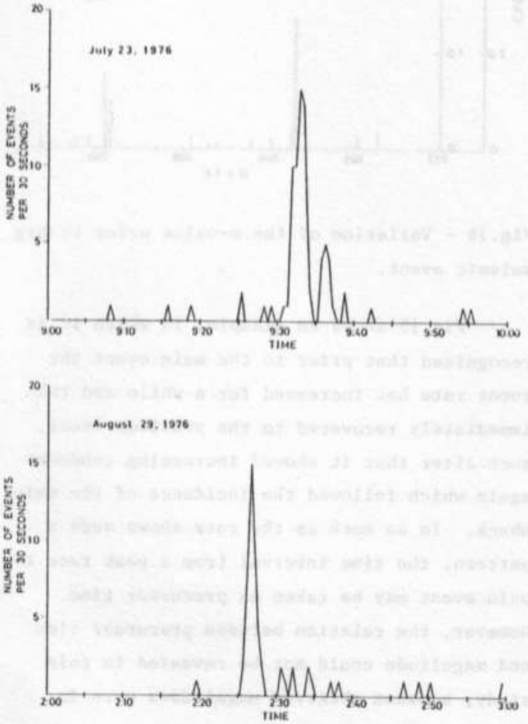

Fig. 13 - Variation of numbers of events per 30 seconds.

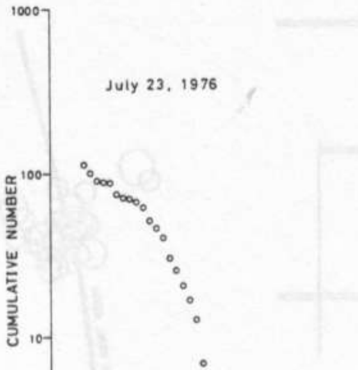

Fig.14 - Magnitude distribution of sequential seismic events.

other is the m-value which represents the power in the Ishimoto-Iida's empirical formual in seismology:

$$N\,dA = k\,A^{-m}\,dA \text{ , ...(5)}$$

where N dA : the number of events with a maximum amplitude traced on the record within the interval from A-1/2dA to A+1/2dA,

k,m : coefficients of distribution.

In Polish coal mines the m-value has been regarded as an interesting measure as well as event rate, Trombik and Zuberek (1977).

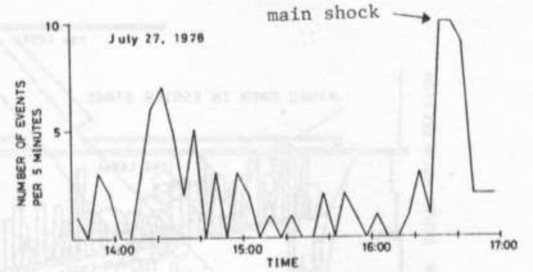

Fig.15 - Variation of number of events per 5 minutes prior to main shock.

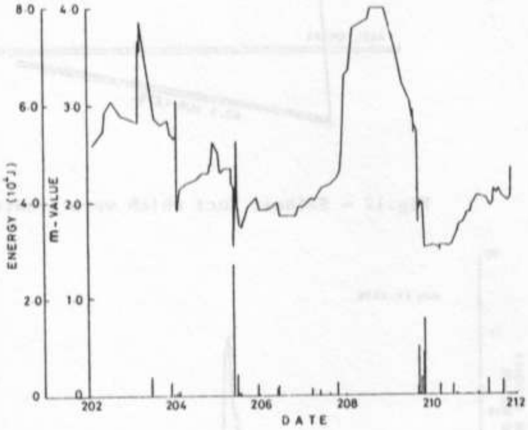

Fig.16 - Variation of the m-value prior to big seismic event.

Fig.15 shows an example, in which it is recognized that prior to the main event the event rate has increased for a while and then immediately recovered to the previous level, soon after that it showed increasing tendency again which followed the incidence of the main shock. In as much as the rate shows such a pattern, the time interval from a peak rate to main event may be taken as precursor time. However, the relation between precursor time and magnitude could not be revealed in this study, because observed magnitudes were in a narrow range.

Concerning the m-value, the number of events must be chosen appropriately for its determination. In this study, each m-value was calculated from every 50 events. Further, in order to maintain an accurate m-value with time, they were determined by adding the last five events immediately after previous 45 events in succession. Fig.16 represents an example of plot of the m-value obtained from the observation. In the diagram the variation of the m-value prior to the big event may be characterized by the drop of the values. So far as such variation is recognized in the m-value, the time interval from a peak value to main event may be regarded as precursor time. The precursor time was surveyed for the same events as these examined by another measure mentioned above. The examination revealed that no specific pattern was recognized for three events among ten of them, and that there was no relation between precursor time and magnitude. However, it should not be concluded hastily from these results that the m-value may be negative for precursive measure, because the m-value could indicate a significant change prior to some big events.

CONCLUDING REMARKS

A seismic method has been applied to deep-level coal mines to investigate seismicity associated with mining. The results of observation extended over four years in Sunagawa Coal Mine showed that the developed measuring system could not only monitor seismicity in a mining panel, but also might be promising for estimating the greatest magnitude of seismic event in the panel from the seismic data measured in an early stage of working period. The distribution of seismic foci and spatial density of seismic energy can be useful to detect a highly stressed zone which coincides often with a source of failure. Furthermore the magnitude of big seismic events, which may bring about the failure of coal face and solid coal pillar, can be estimated by the b-value and the seismic energy release rate. On the other hand the precursive measures of impending failure have not yet been detailed, although the event rate and the m-value were preferable for predicting impending failure. It is obvious that small seismic events which must be informative for prediction can not be distinguished from ground noises at a long distance, because the seismic wave with high frequency may be significantly attenuated along the path from source to measuring point. Therefore, a proper choice of the dimension of seismic array may be essential for the prediction together with appropriate selection of the frequency range of the measuring devices.

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